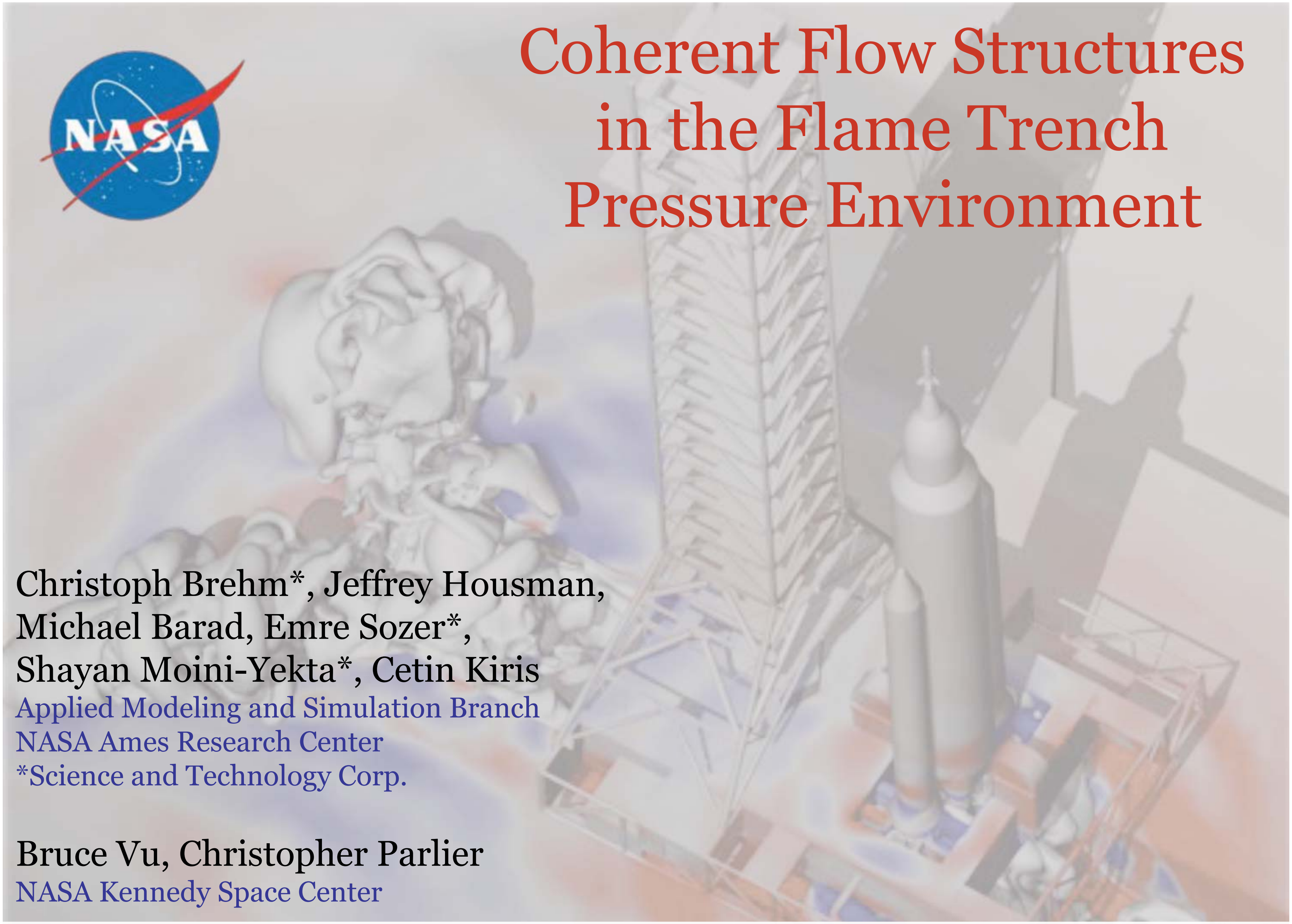


Coherent Flow Structures in the Flame Trench Pressure Environment

Christoph Brehm*, Jeffrey Housman,
Michael Barad, Emre Sozer*,
Shayan Moini-Yekta*, Cetin Kiris
Applied Modeling and Simulation Branch
NASA Ames Research Center
*Science and Technology Corp.

Bruce Vu, Christopher Parlier
NASA Kennedy Space Center

Outline

Motivation/Introduction

Introduction to the launch environment flow and jet impingement problem.

Computational Methods

Overview of tools and setup used for simulations.

Jet Impingement Model Problem

Analysis of jet impingement problem.

Falcon Heavy: Pressure Environment

Final application of pressure environment analysis.

Summary & Future Work

Overview of results and what tasks lie ahead.

Motivation:

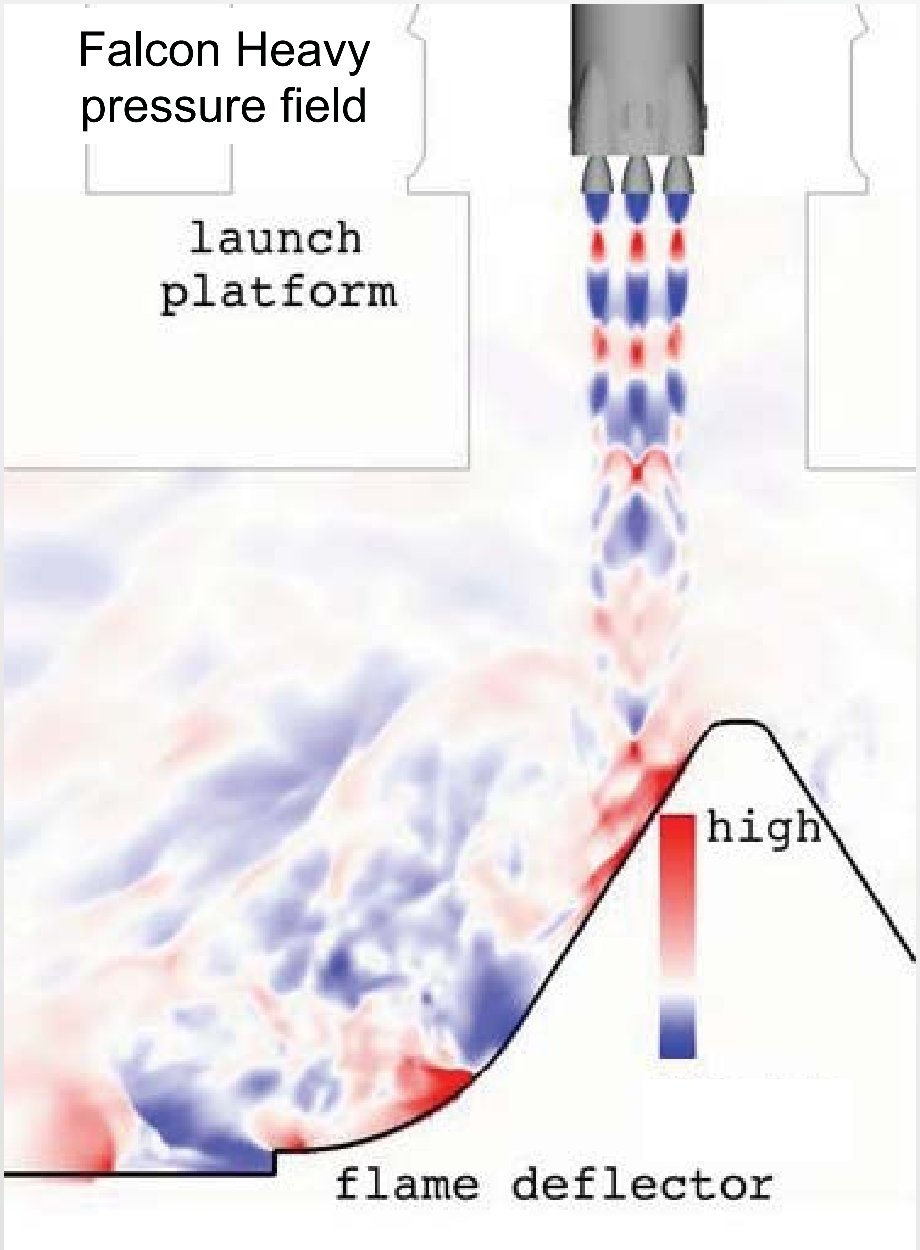
The Launch Environment

Significant resources have been spent to develop the materials and structure to withstand the harsh conditions of vehicle launches.

The launch environment is highly complex in terms of geometric details and flow physics.

Jet Impingement Problem:

Pressure Environment



Motivated by CFD prediction requirements of launch pressure environments in the flame trench.

damage after STS-124 launch

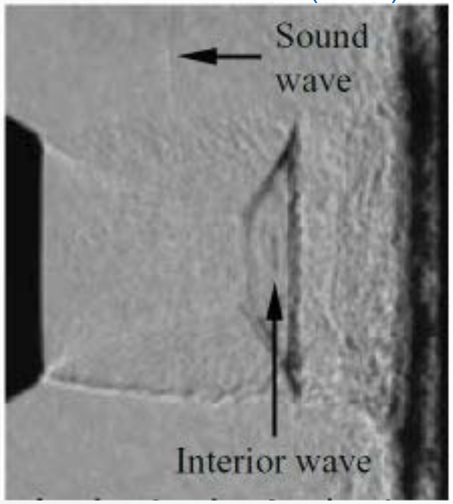
Background:

Jet Impingement Problem

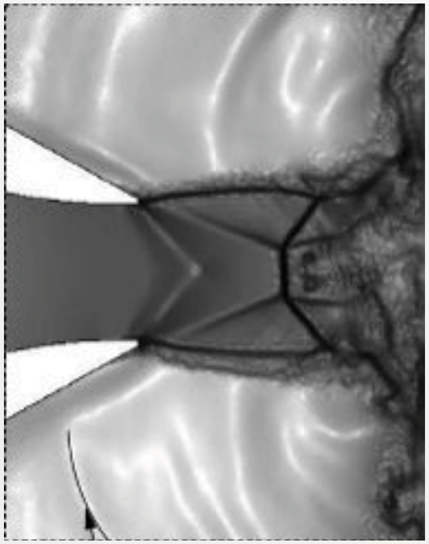
Supersonic jet impingement is an important problem for rocket launch and vertical take off and landing aircraft

- Complex instabilities when jet impinges on plate
- Tone generation for free jets is well documented
  (Tam (1990), Panda (1999), …)
- Various studies on shock-wave oscillations
  (Henderson et al. (1993,2002,2005), Nakatogawa et al. (1971), Ginzburg et al. (1970), …)
- Tone generation for certain nozzle pressure ratios and plate to nozzle distances
  (Krothapalli et al. (1999), Henderson et al. (2005), …)
- Instability depends on plate location in the shock cell structure of corresponding free jet and standing-off shock
  (Henderson et al. (2005))
- Feedback model: Downstream convected large scale coherent flow structures and upstream propagating pressure waves produce resonance
- Approximate formula for instability frequencies
  (Dauptain et al. (2012), Henderson and Powell (1993), Powell, Ho and Nosseir (1981), etc.)

Exp.: Shadow photograph
Henderson et al. (2005)



LES: Density Grad
Dauptain et al. (2012)



M=2.1, L=2×D, NPR=4

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Approach:

Post-Processing

- **POD** results in a decomposition of the flow field into a set of basis functions that capture most of the flow energy as defined by a user-defined norm with the least number of modes*

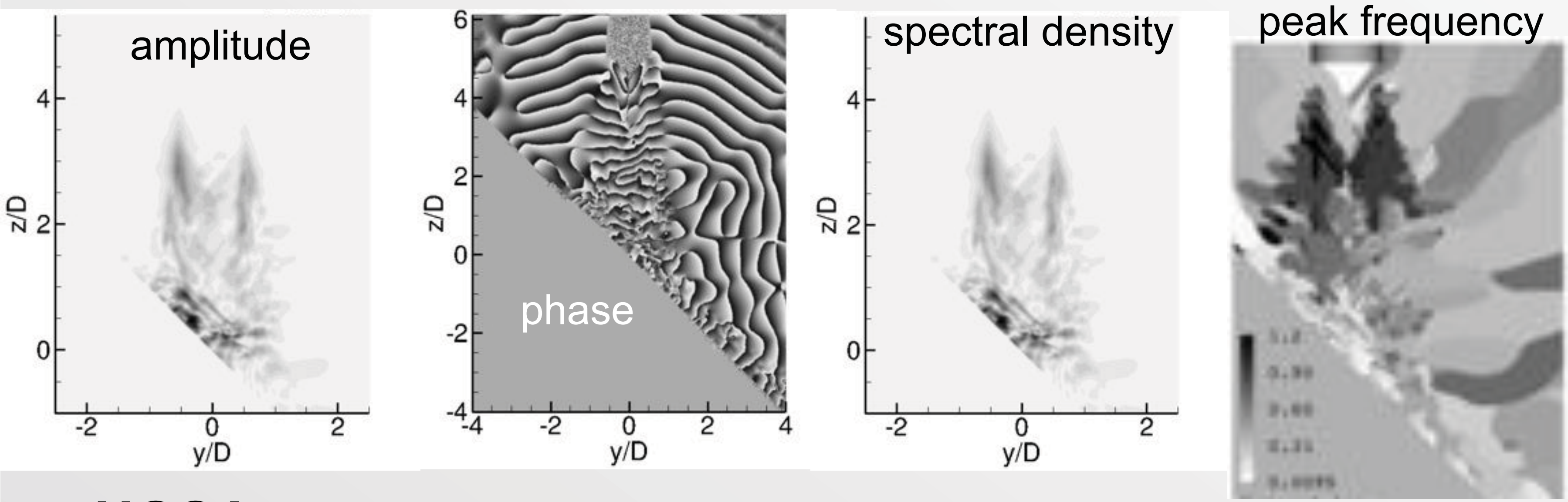
$$\vec{q}(\vec{x},t) \approx \sum_{n=0}^{I} a^{(n)}(t)\vec{\chi}^{(n)}(\vec{x})$$

*Rowley(2001), Freund and Colonius (2002)
**Lumley(1967), Sirovich (1987), Chatterje (2004)
***Nonomura et al (2011)

  - Used snapshot method** in temporal domain
  - Vector norm (energy) with
    q_k=[p,u,v,w,$T^{0.5}$] and ω_k=[1,0,0,0,0]

$$|\vec{q}|^2 = \int_V \left(\sum_{k=1}^{N_q} \omega_k\, q_k q_k \right) d\vec{x}$$

- **DFT** used to analyze time-spectral characteristics of pressure field

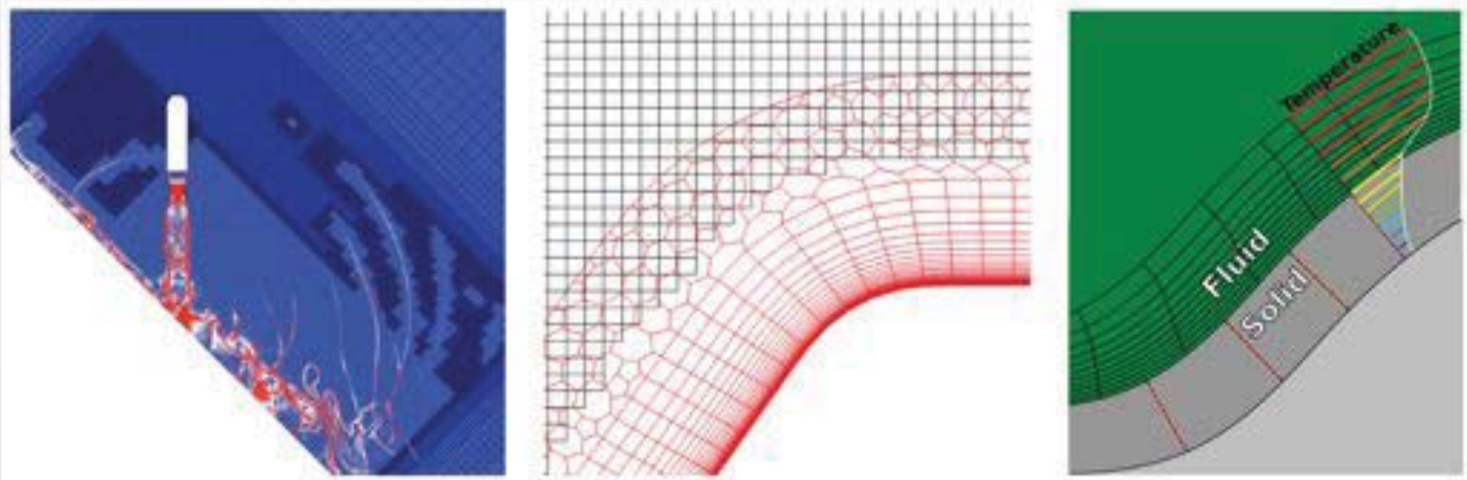


- **HOSA** results shown in paper (phase speed and coherence length)

Approach:

LAVA Solver

Launch **A**scent and **V**ehicle **A**erodynamics



- Developed by authors at NASA Ames Research Center.
- Supports Cartesian AMR, block structured-curvilinear overset, and unstructured arbitrary polyhedral cells.
- Sharp interface immersed-boundary representation of geometry.
- Cell centered finite-volume and finite-difference formulation.
- Explicit and implicit time-integration.
- Multi-species capability with user-specified equations of state.
- Automatic volume gridding requiring only a surface triangulation.

*Kiris et al.(2014), Brehm et al. (2014), Sozer et al. (2014), Housman et al. (2014), Moini-Yekta (2012,2013)

Approach:

Investigate Level of Fidelity for Pressure Environment Simulations

- Slowly increase complexity of CFD model to examine assumptions:
  - Inviscid
  - Viscous (ILES, SA-DES), slip wall BCs*
  - Viscous (ILES, SA-DES), no-slip wall BCs

→ What can these CFD approaches capture?

- Want fast turn-around times while maintaining high degree of accuracy
  - Reduce grid generation time

    → immersed boundary methods essentially eliminate manual grid generation process
  - Reduce run time

    → block structured mesh provides optimal memory layout

*Dauptain *et al.*, "Large Eddy Simulation of Supersonic Impinging Jets", AIAAJ, 2012

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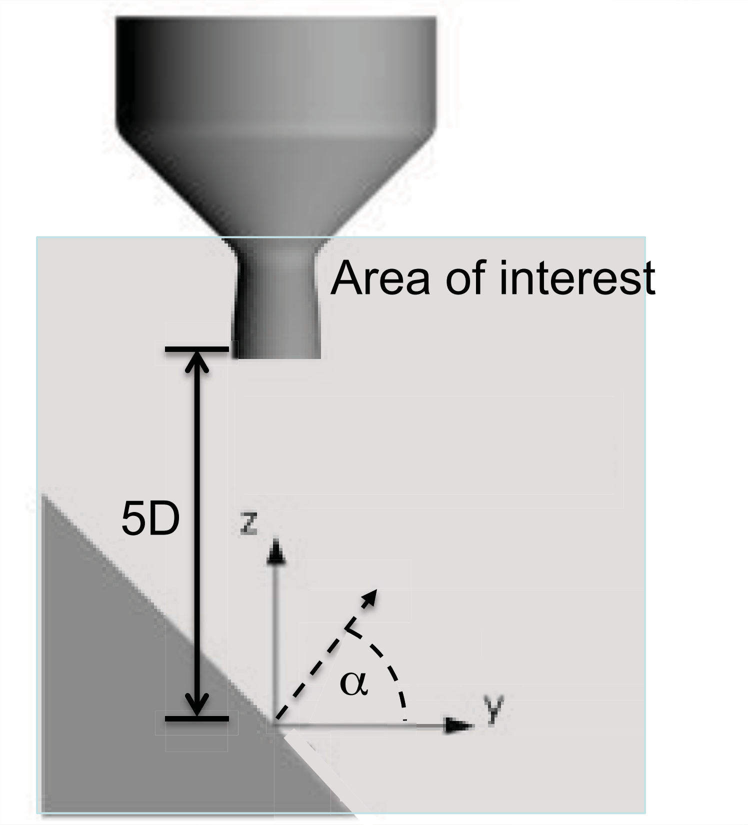
Jet Impingement Problem:

Computational Setup

- Collaboration with JAXA**
- Conditions based on experiments by Nakanishi et al. at the UT-Kashiwa hypersonic and high-temperature wind tunnel*
- M=1.8, air at T=300K (cold)
- $Re = V_e D/\nu = 1.6\times10^6$
- 200-400 million grid points
- Nozzle-to-plate distance 5D
- Impingement angle α



Flow conditions at nozzle exit and percent differences with perfectly expanded jet:

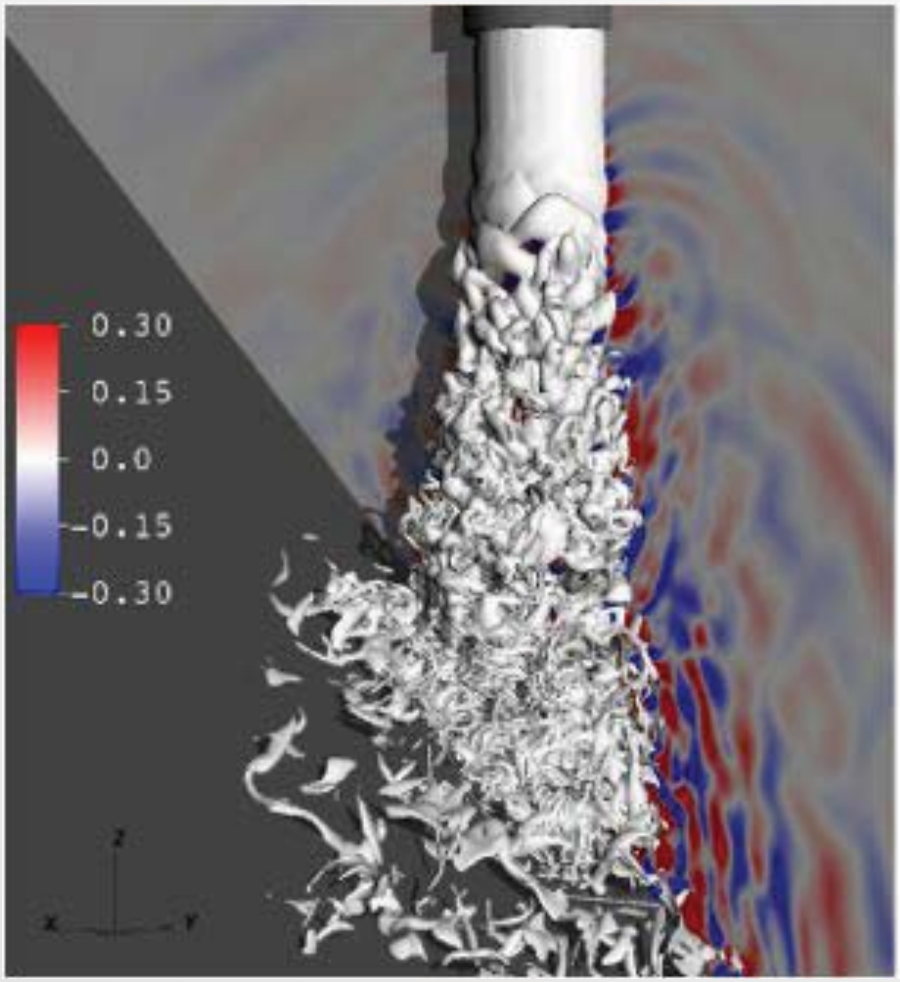
	Mach number	pressure, p_{ref} [Pa]	exit velocity, V_e [m/s]
exit conditions	1.8045	100,794	488.14
difference	~0.25%	~0.52%	~0.24%

*Nakanishi et al., “Acoustic characteristics of correctly-expanded supersonic jet impinging on an inclined at plate”, AJCPP2012-129
**Tsutsumi et al. 2012, **Nonmura et al. 2010 & 2011

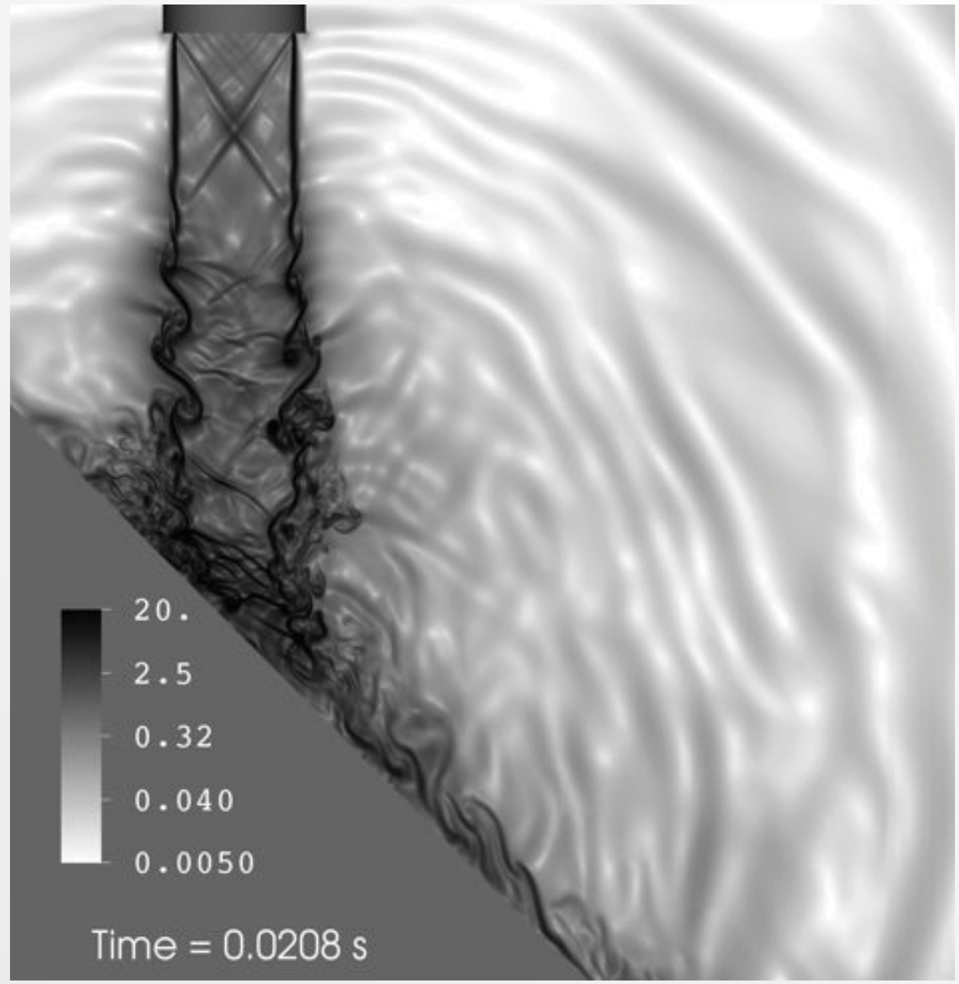
Jet Impingement Problem:

Unsteady Flow Field

dilatation & $|\omega|D/V_e \approx 8.3$



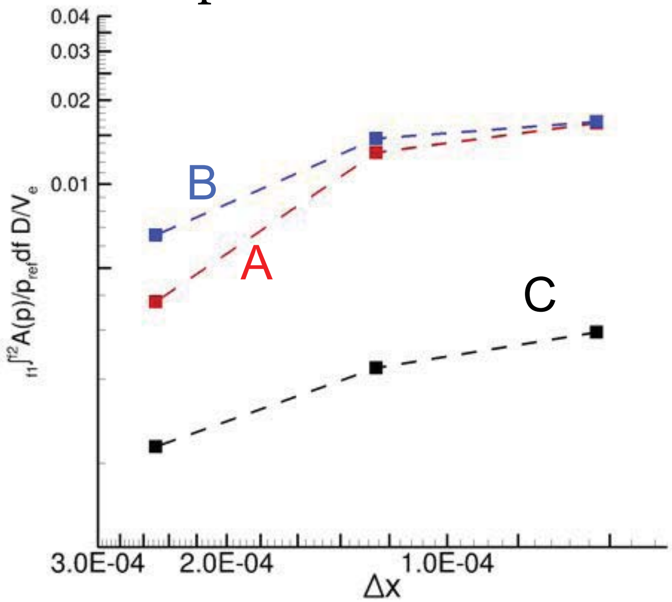
pseudo-Schlieren



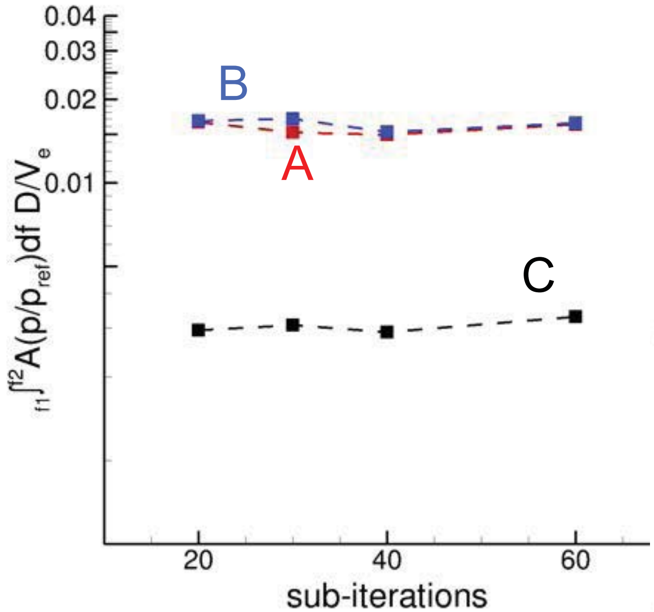
Jet Impingement Problem:

Grid Convergence

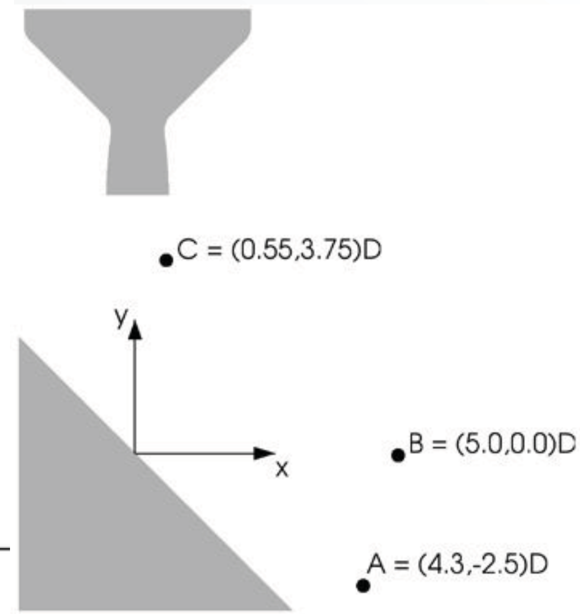
Spatial Resolution



Sub-Iterations



Point Probes



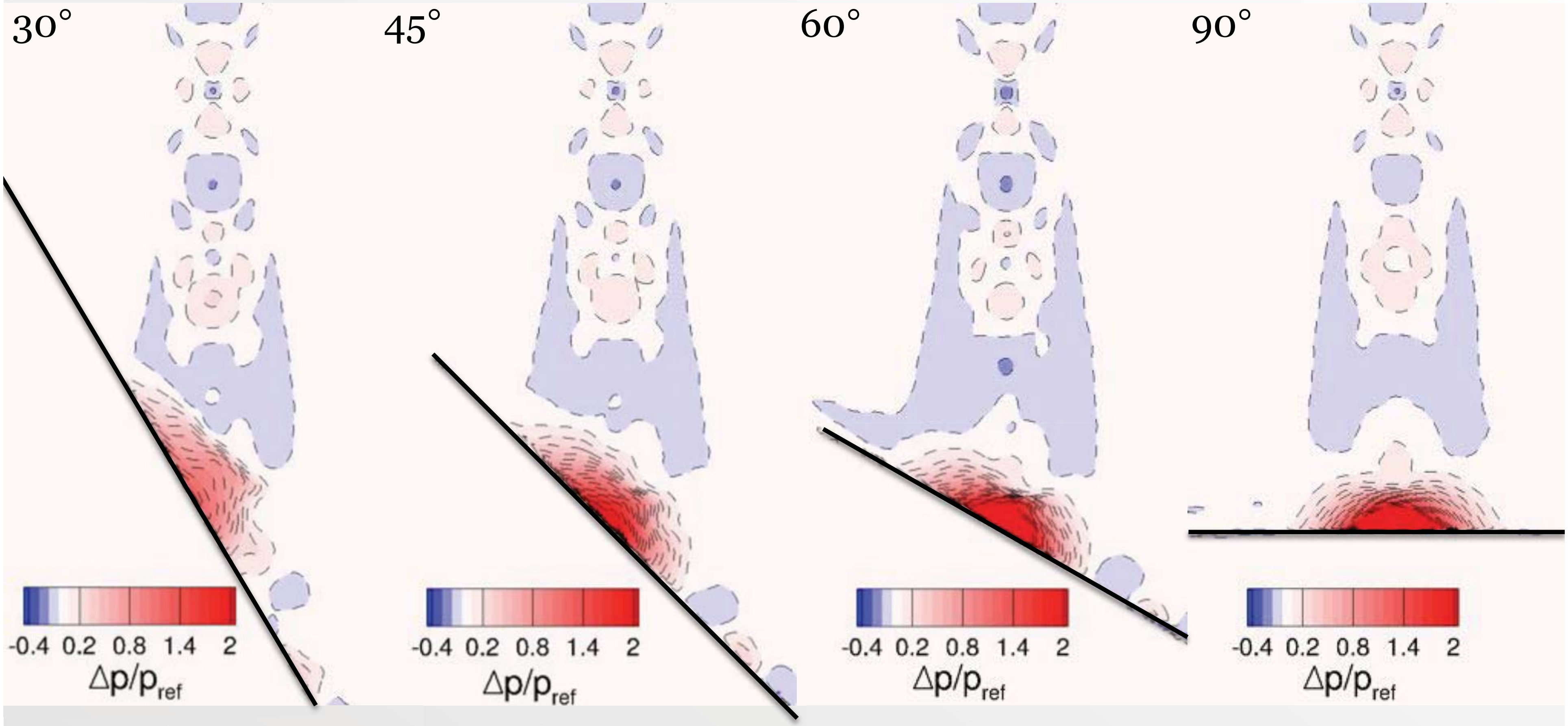
- Error convergence study w.r.t. spatial discretization, sub-iterations, time-step*
- Thorough verification study of LAVA in Moini-Yekta et al.**,***
- Grid resolution sufficient until approximately St=3-4
- Much finer mesh than Dauptain et al.

*Housman et al. “Space-Time Convergence Analysis of a Dual-Time Stepping Method for Simulating Ignition Overpressure Waves“ ICCFD6, 2010
**Moini-Yekta et al. “Verification and Validation Studies for the LAVA CFD Solver”, AIAA Paper, San Diego, June 23-27th, 2013
***Kiris et al. (2014)

Jet Impingement Problem:

Mean Flow

Mean-Pressure Contours:



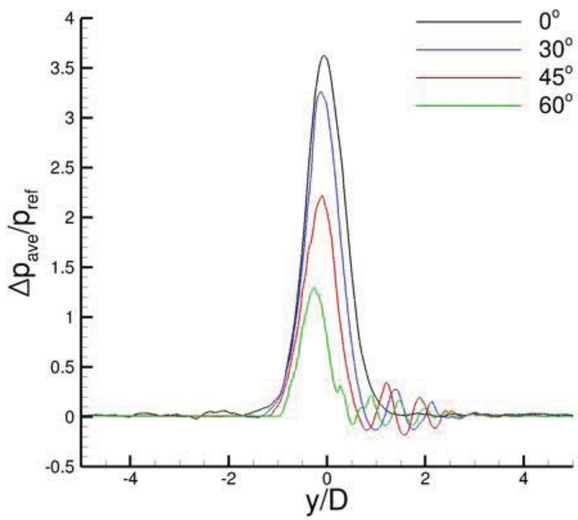
- Flow is mildly over-expanded
- Shock structure on the impingement surface
- Impingement pressure increases with angle

Jet Impingement Problem:

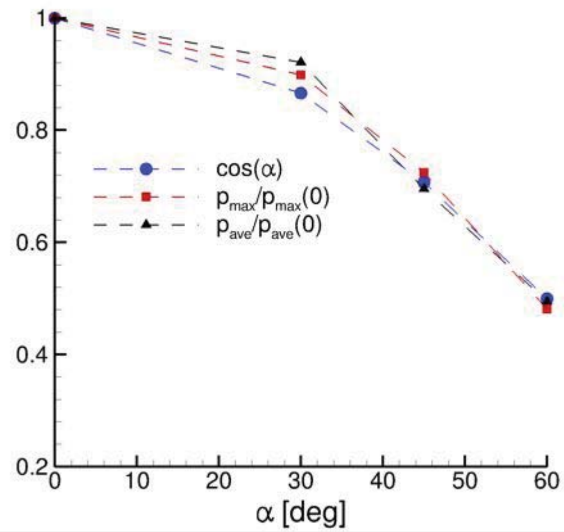
Mean Flow:

Pressure Distribution in x=0 cutting plane

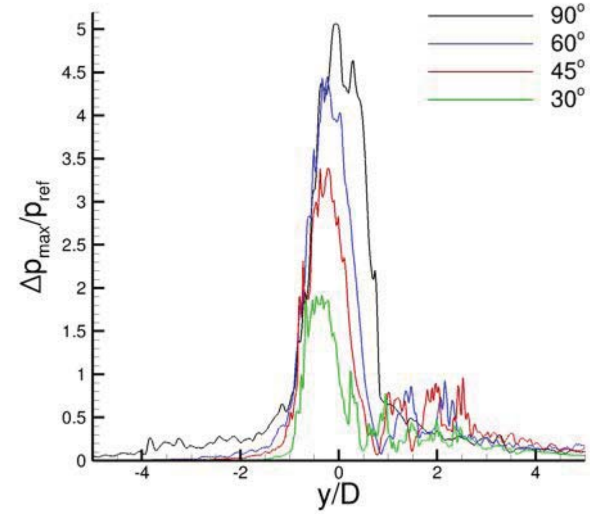
time-averaged



approximated



maximum



$$p_{\max}/p_{ref} = \max\{\frac{p(\vec{x},t)-pref}{pref}: 146<\frac{U_{ref}t}{D}<365\}$$

- Maximum in time-averaged pressure distribution analytically estimated (≈3% error) (see for example Allgood for application to flame deflector)
- CFD needed to predict spatial pressure distribution and unsteadiness
- Maximum surface pressure is approximately 40-50% higher than time-averaged maximum surface pressure

Allgood, D. and Ahuja, V., "Computational Plume Modeling of Conceptual ARES Vehicle Stage Tests", AIAA Paper 2012
Launcher/Transport Branch, "Development of Design Criteria for Saturn V Flame Deector", NASA-TM, 1965

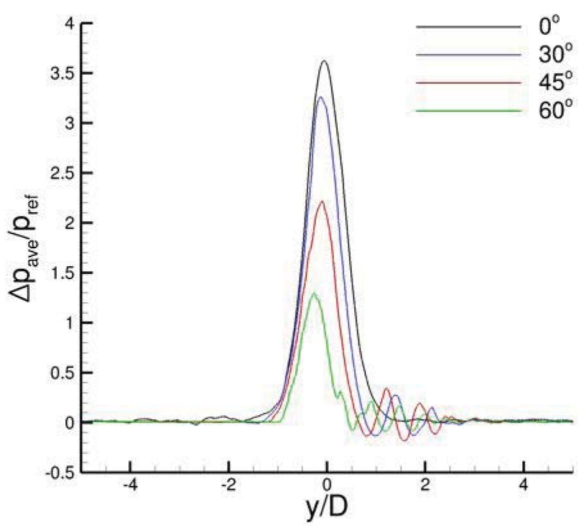
Jet Impingement Problem:

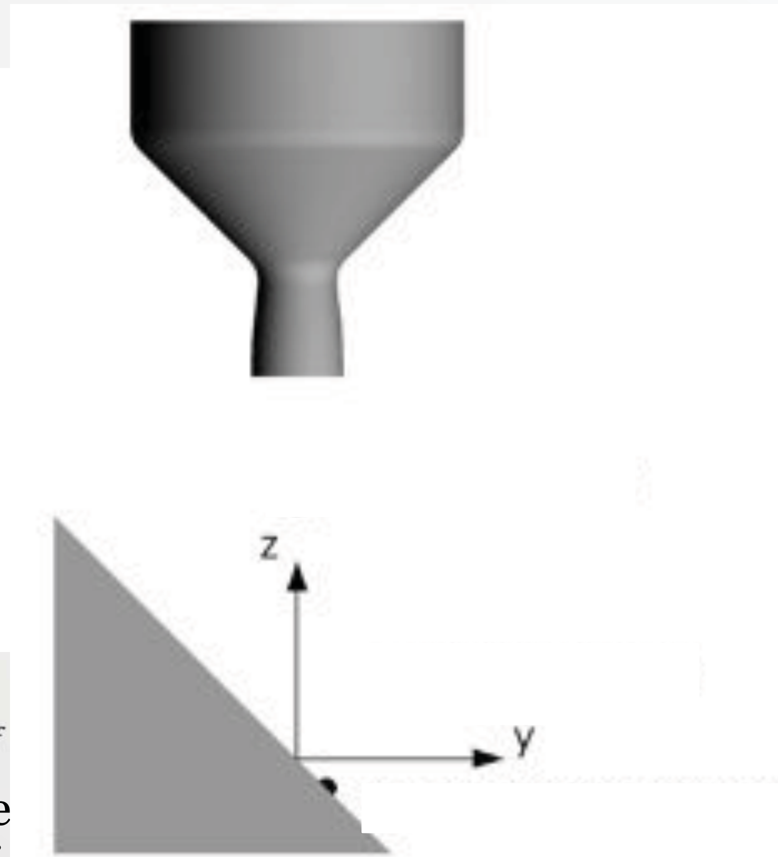
Mean Flow:

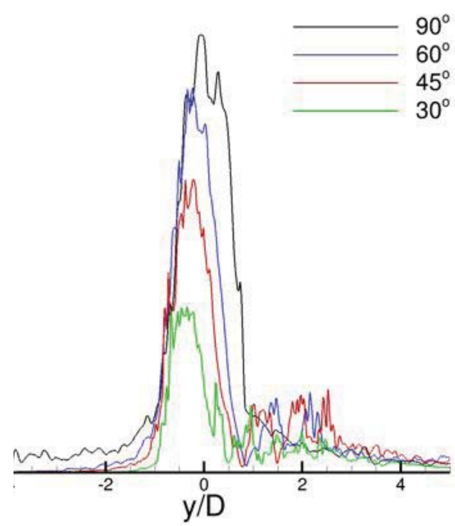
Pressure Distribution in x=0 cutting plane

time-averaged

maximum







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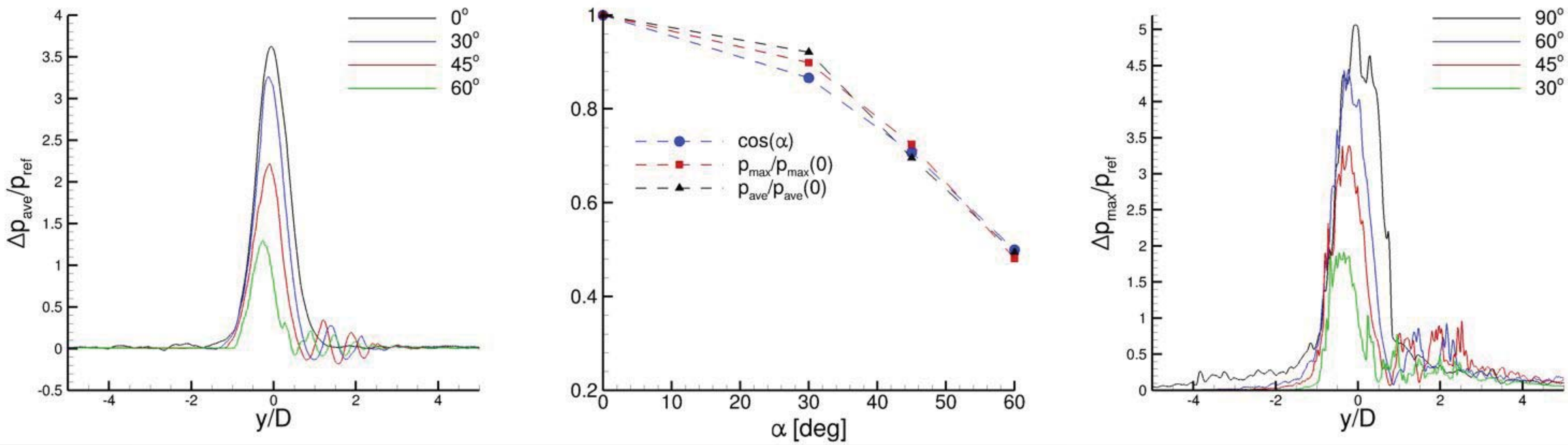
Mean Flow:

Pressure Distribution in x=0 cutting plane

time-averaged approximated maximum



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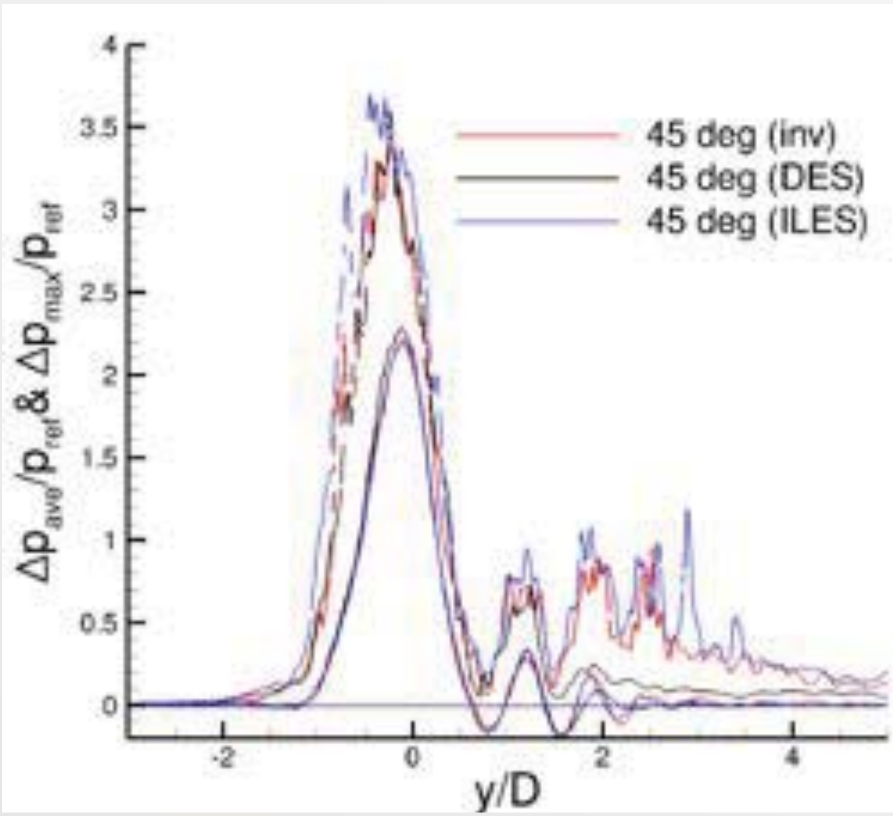
Launcher/Transport Branch, "Development of Design Criteria for Saturn V Flame Deector", NASA-TM, 1965

Jet Impingement Problem:

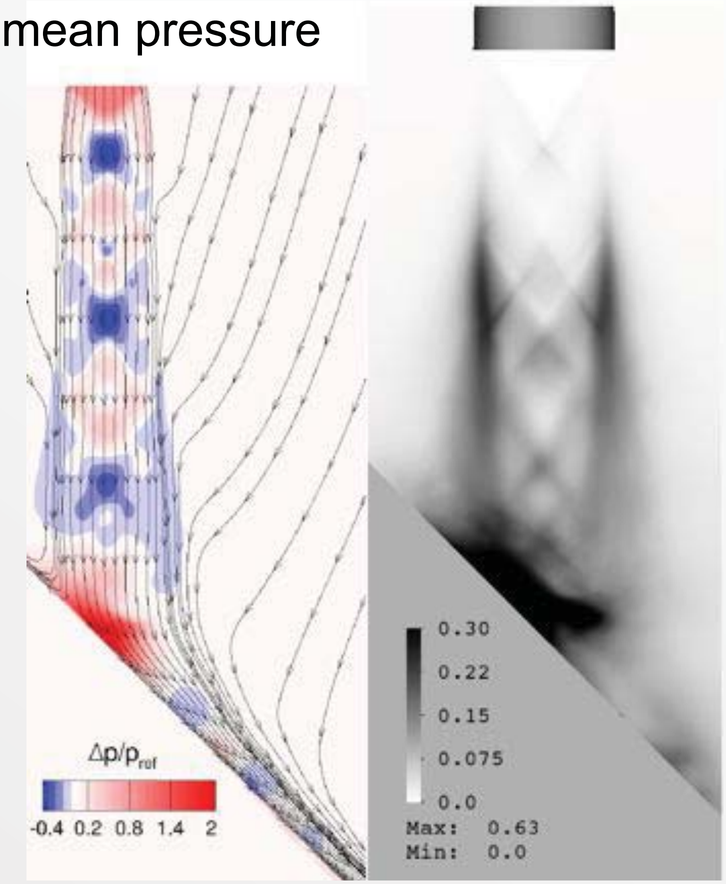
Inviscid vs. Viscous

Max. surface pressure



Streamlines and mean pressure

pressure rms



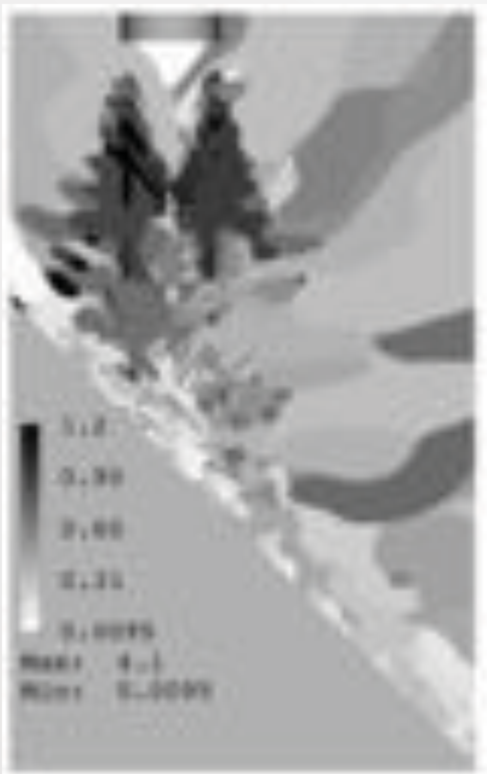
ILES

- DES near the wall dampens pressure oscillations
- Very close agreement between viscous and inviscid results

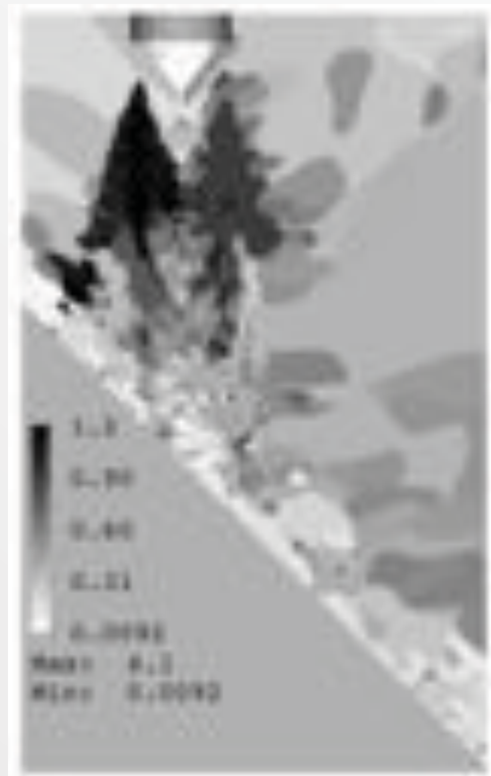
Jet Impingement Problem:

Peak Frequencies

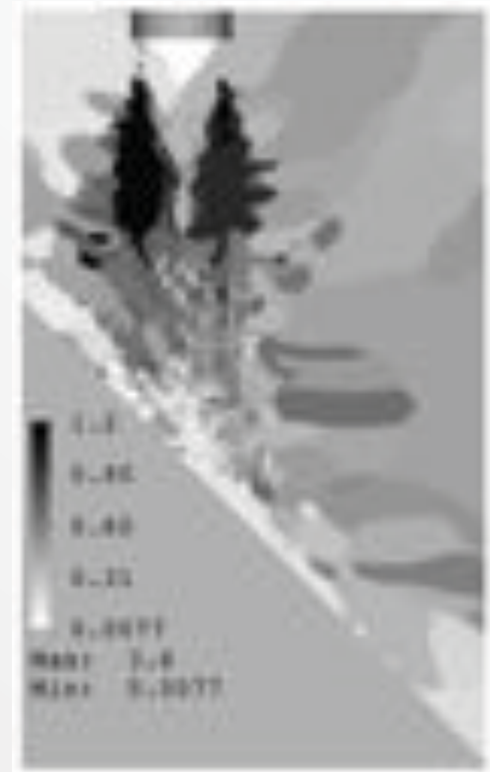
Inviscid



ILES



DES

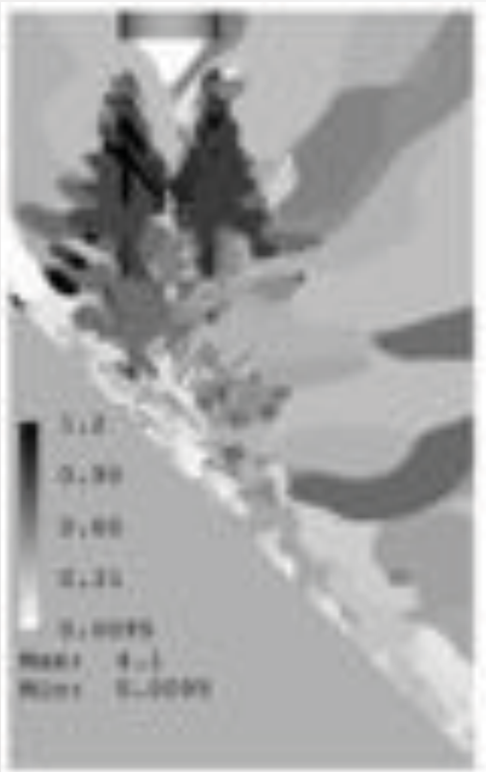


- General features of peak frequency distributions are very similar
- Several reasons for asymmetry in distribution:
  Noisy spectra, statistically not yet converged, (m=3)-mode, higher excitation from up-slope reflected waves

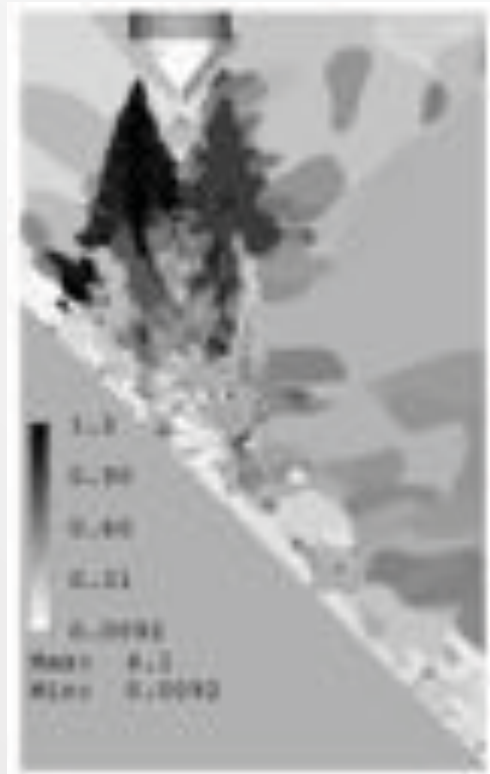
Jet Impingement Problem:

Peak Frequencies

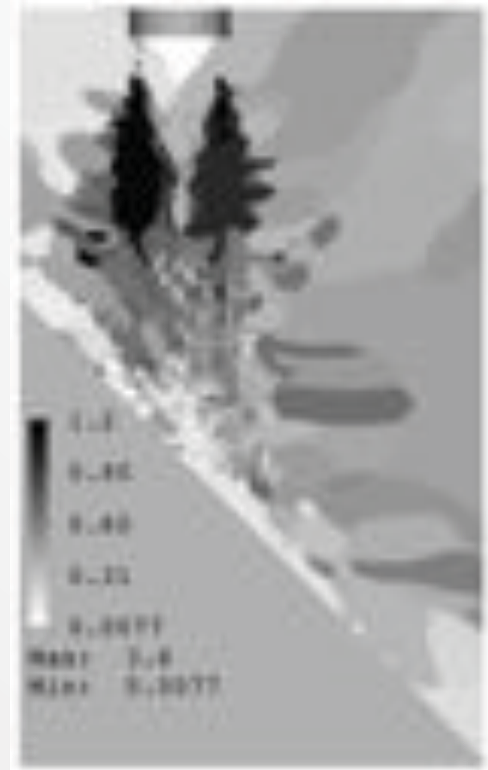
Inviscid



ILES



DES



- Several reasons for asymmetry in distribution:
  Noisy spectra, statistically not yet converged, (m=3)-mode, higher excitation from up-slope reflected waves
- General features of peak frequency distributions are very similar

Jet Impingement Problem:

Peak Amplitudes

Inviscid

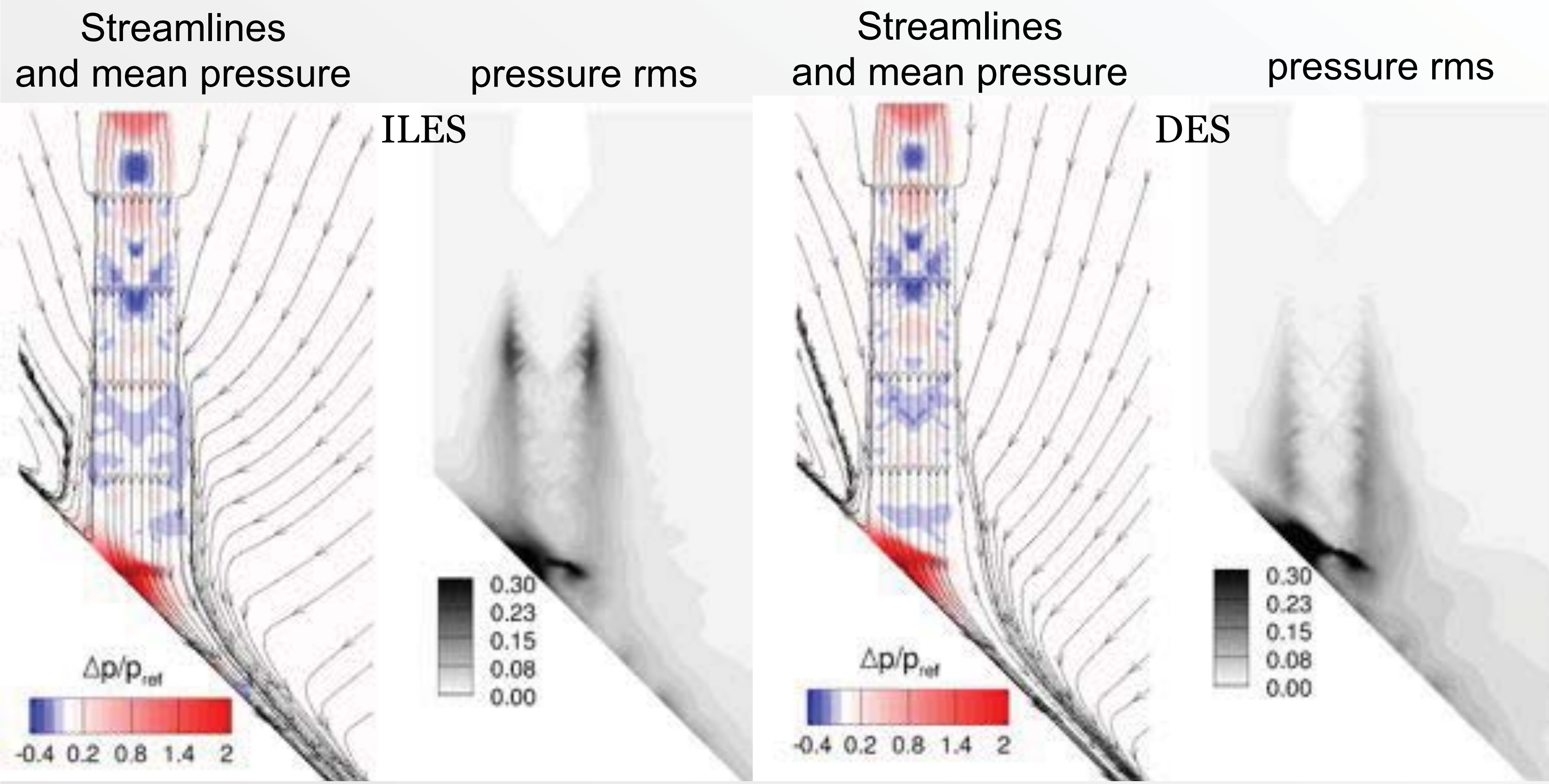
ILES

DES

- All three CFD models display similar distributions
- Reduced amplitudes for DES downstream of the impingement location

Jet Impingement Problem:

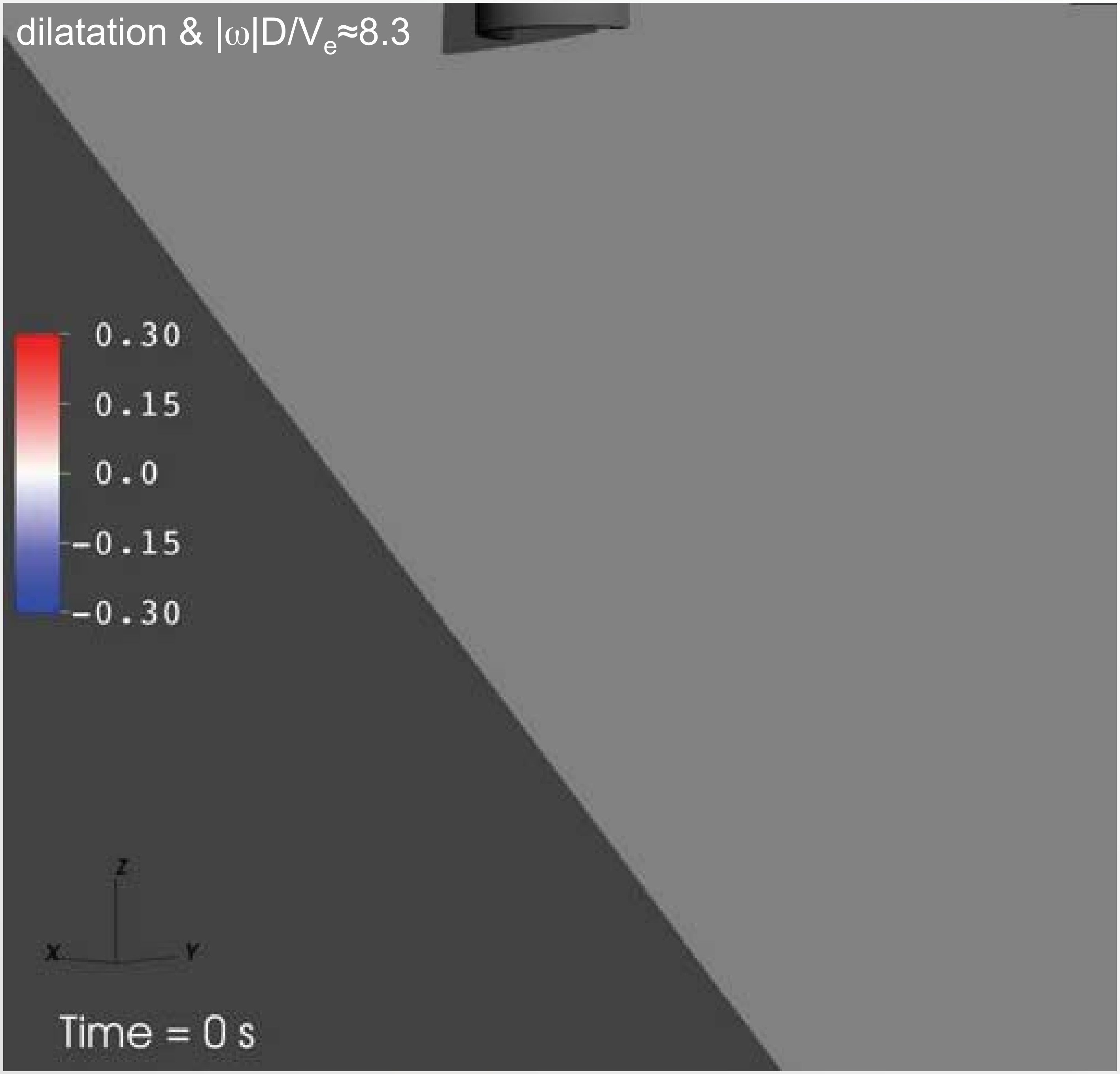
No-slip Wall BCs



Note: curvilinear overset grid system

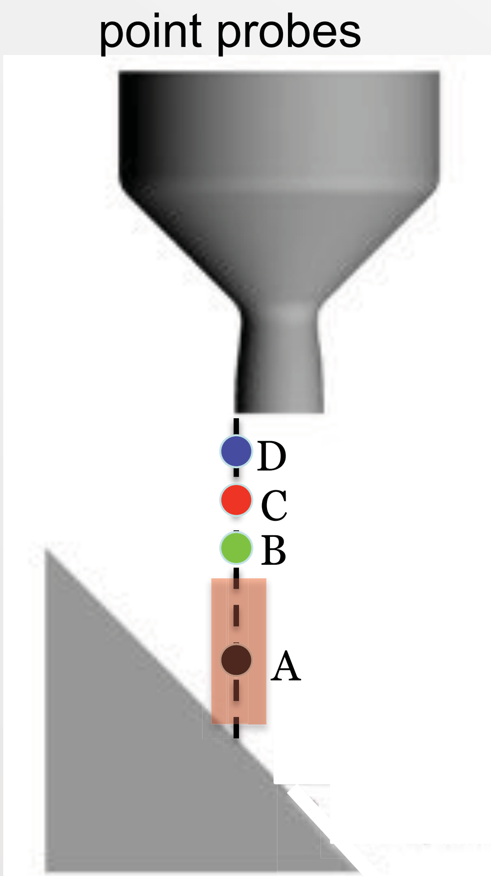
- No separation on impingement plane
- Streamlines and pressure rms values are very similar
- Slightly more diffused solution due to coarser grid and metric terms
- Eddy viscosity from DES model seems to affect unsteadiness in shear layer

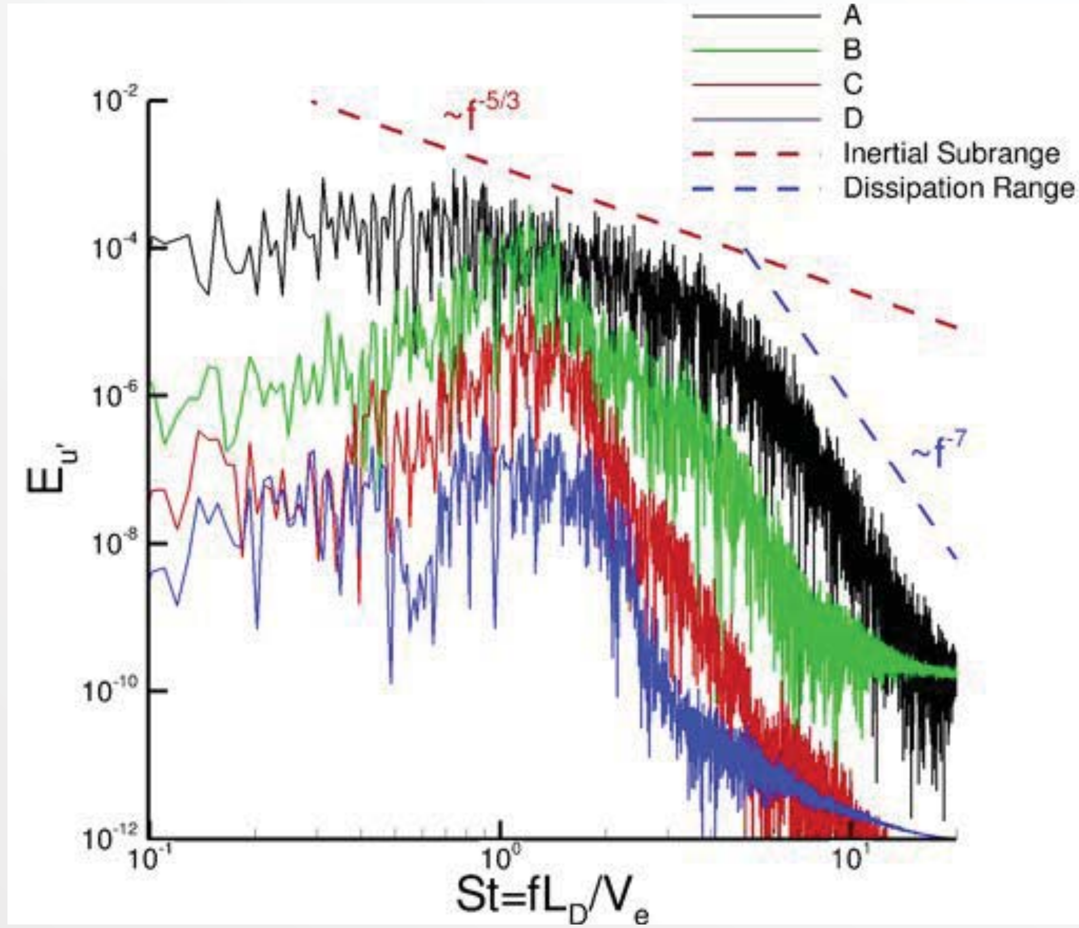
Jet Impingement Problem:



Jet Impingement Problem:

Velocity Power Spectra (ILES)

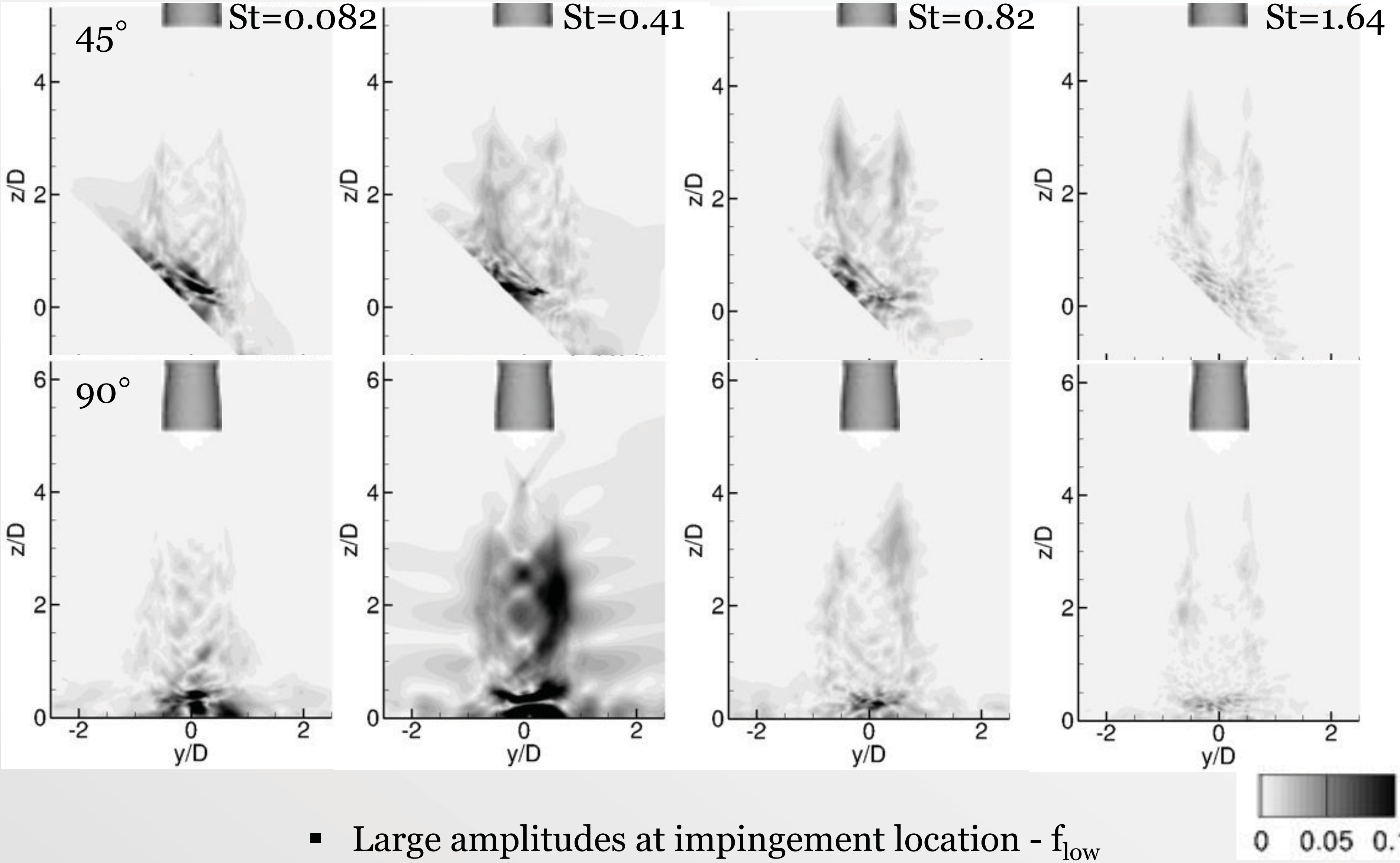




- Energy spectrum fills up from D to A (laminar-turbulent transition process)
- Points within red-shaded region show similar spectra
- Well resolved until approximately St=3-4
- Frequencies correspond well to results in literature (Michalke (1984)) $\omega\Theta_C/U_o \approx 0.1\text{-}0.2$ for m=0 and m=1 (azimuthal modes)

Jet Impingement Problem:

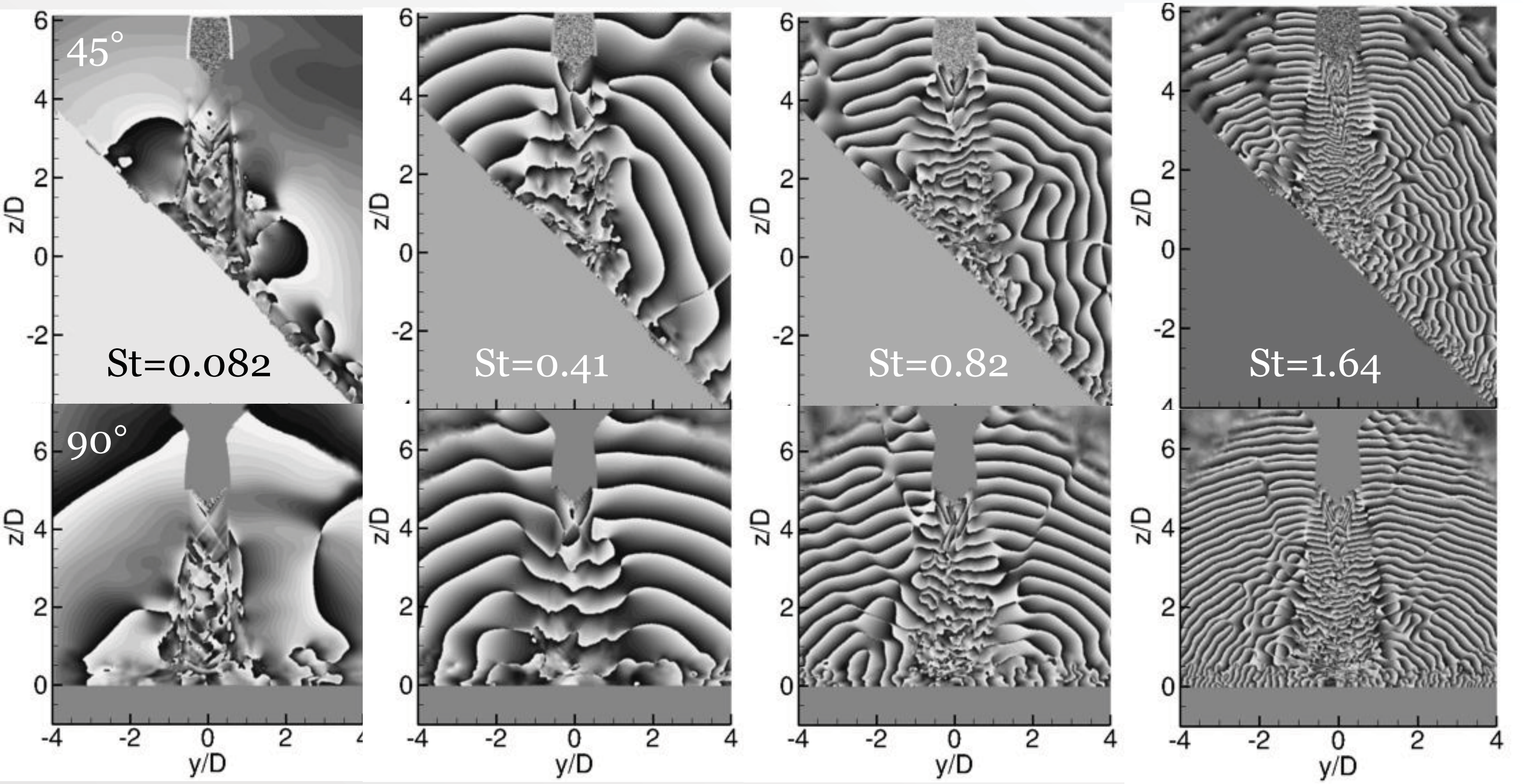
Spectral Analysis: Amplitude



- Large amplitudes at impingement location - f_{low}
  - Broad spectrum in shear layer – f_{high}

Jet Impingement Problem:

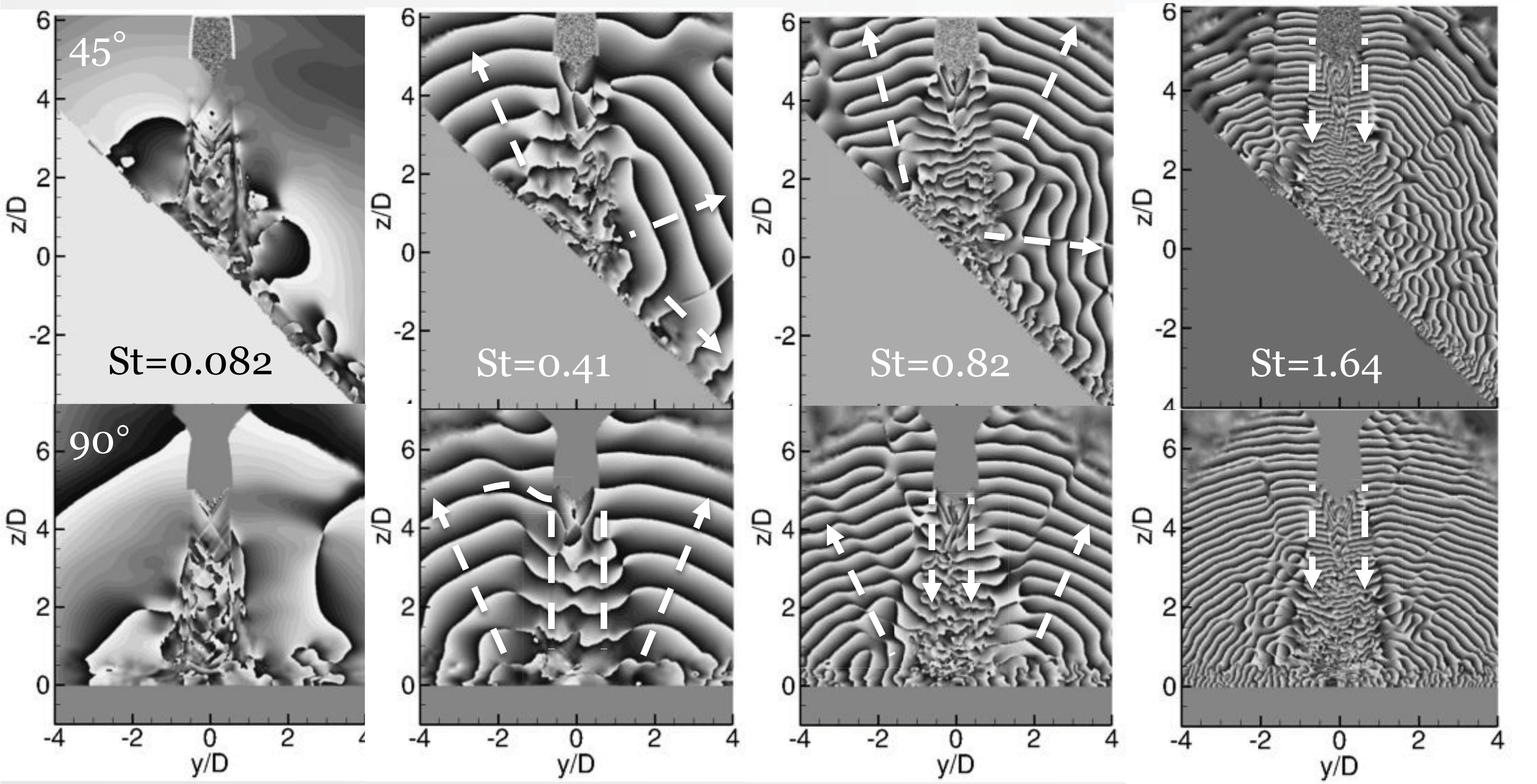
Spectral Analysis: Phase



- Provides overview of directionality of wave propagation
  - For acoustic waves as well as instability waves
- Shear layer waves close to nozzle lip appear to be unaffected by impingement angle for St=1.64, stronger effect for St=0.41

Jet Impingement Problem:

Spectral Analysis: Phase



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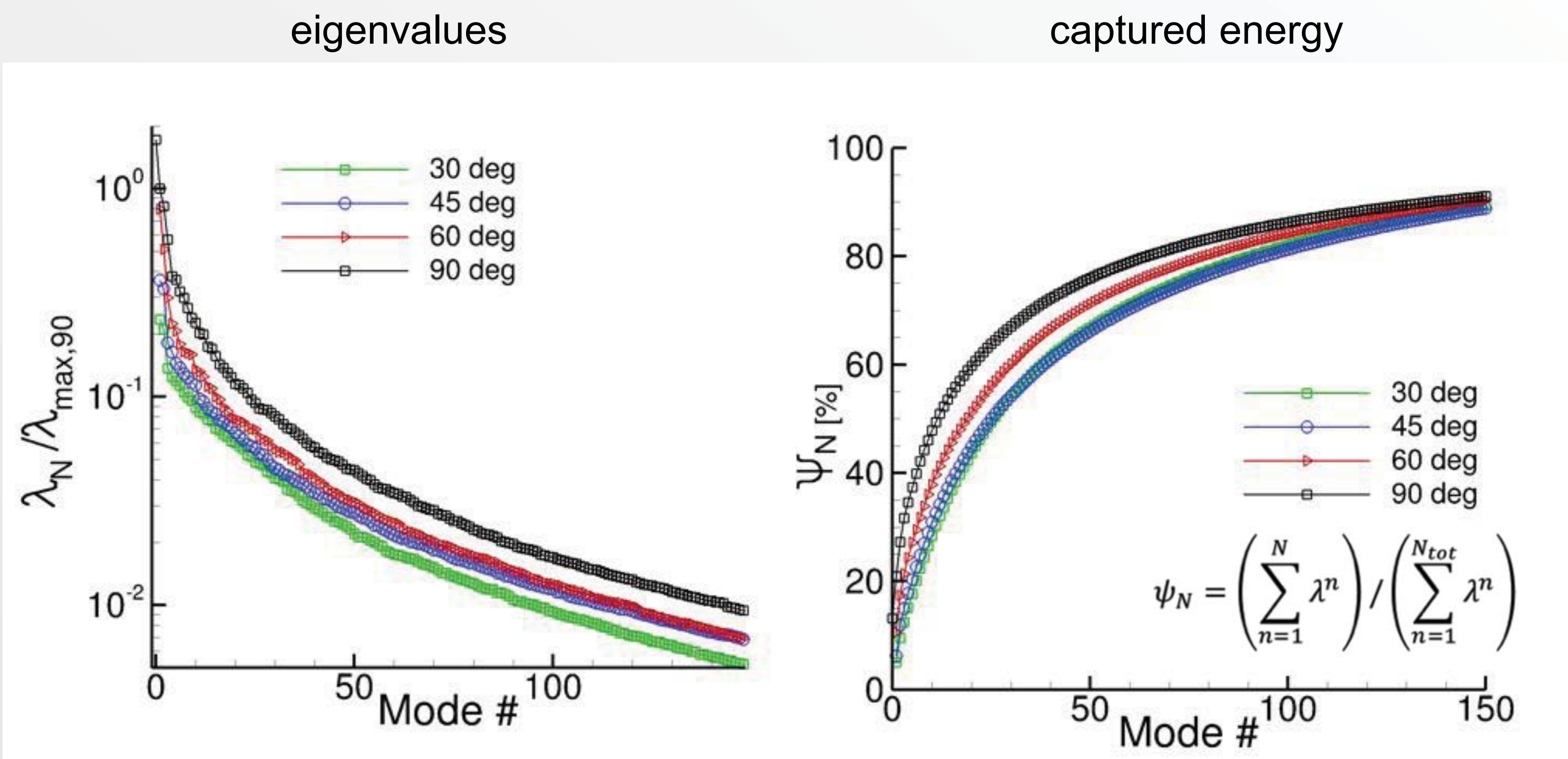
Jet Impingement Problem:

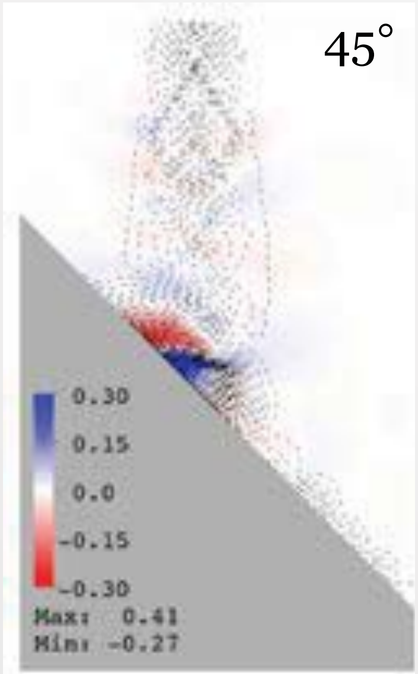
Proper Orthogonal Decomposition



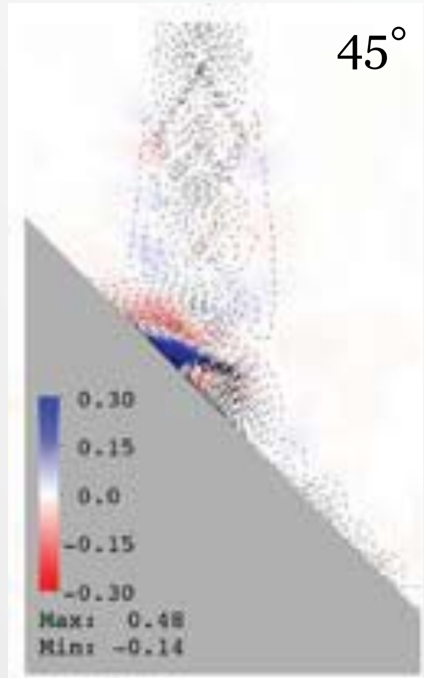
- Stronger coherence with increasing impingement angle
- ~20/50 modes capture 60/80% of energy (p) for 90°

Jet Impingement Problem:

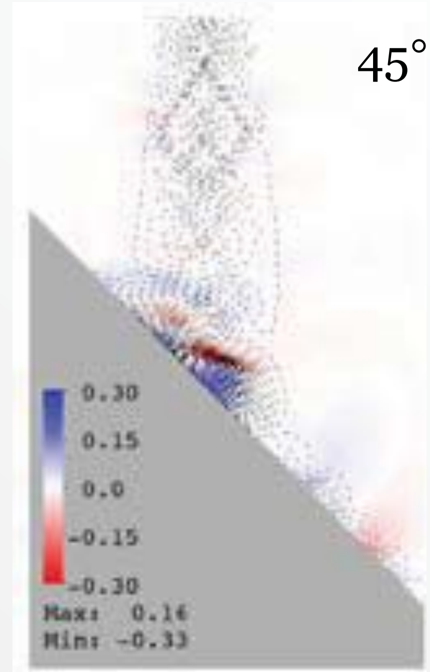
POD modes



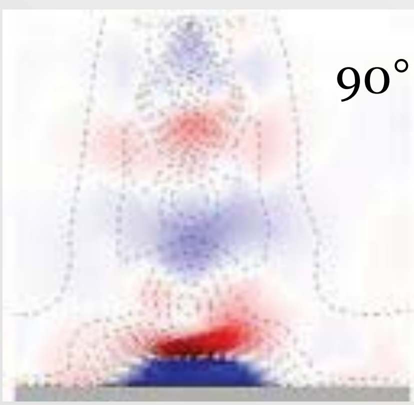
mode 1



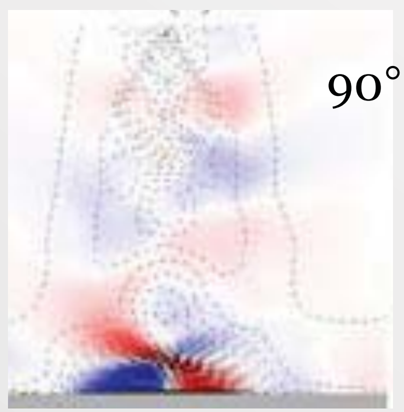
mode 2



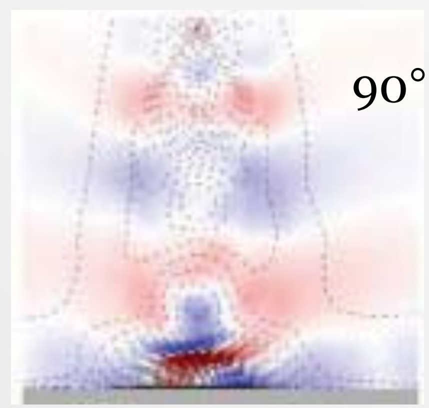
mode 3



mode 1



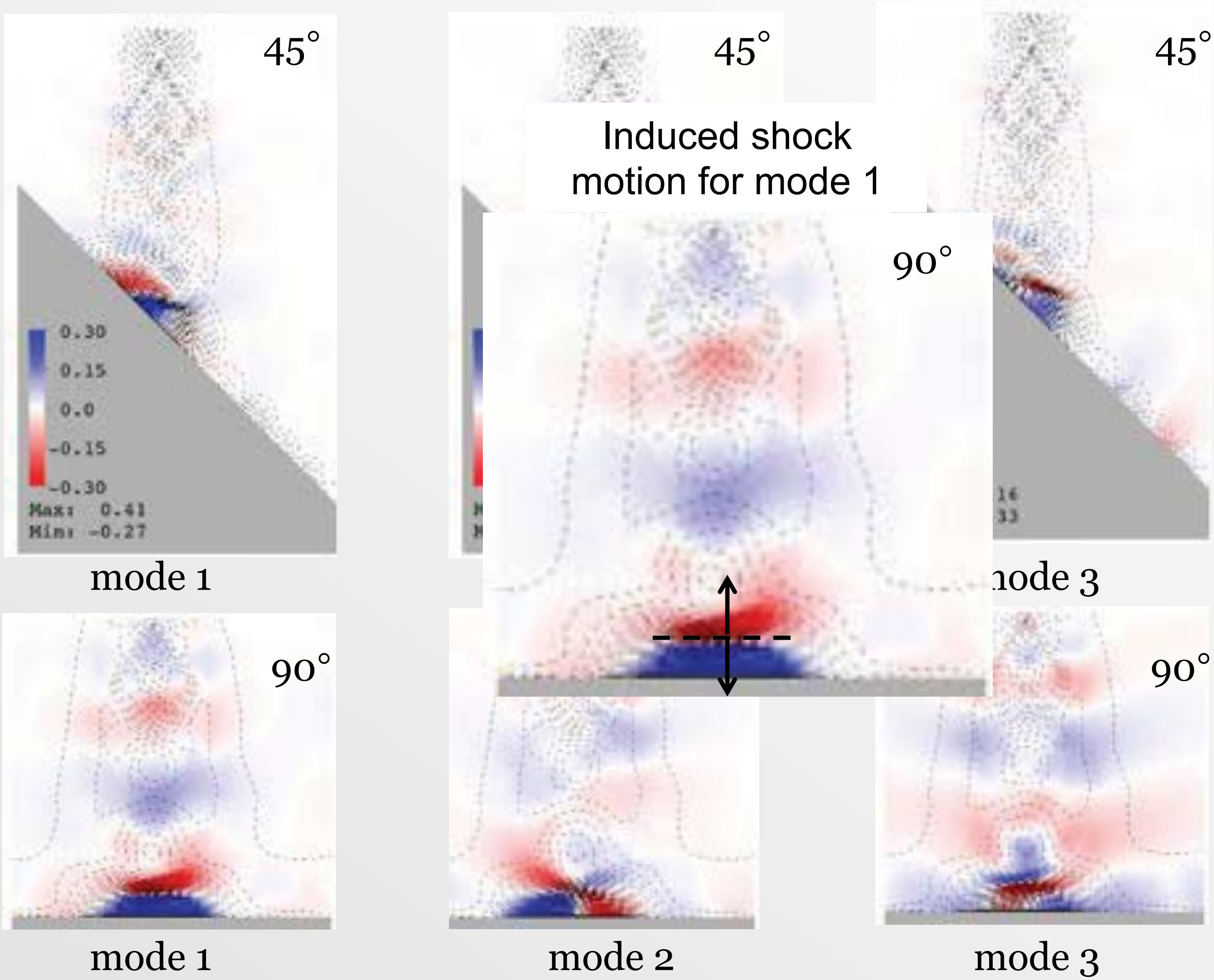
mode 2



mode 3

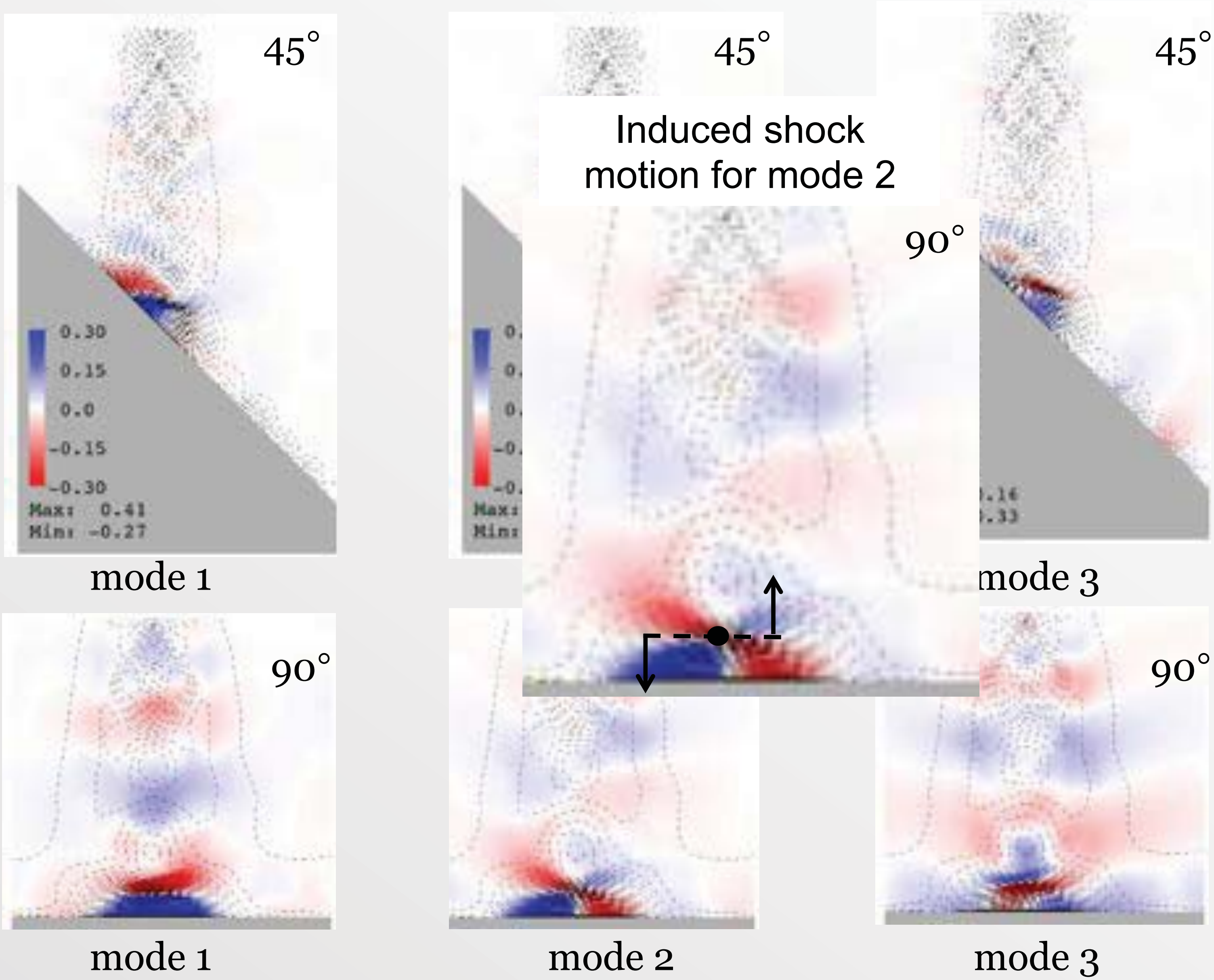
Jet Impingement Problem:

POD modes



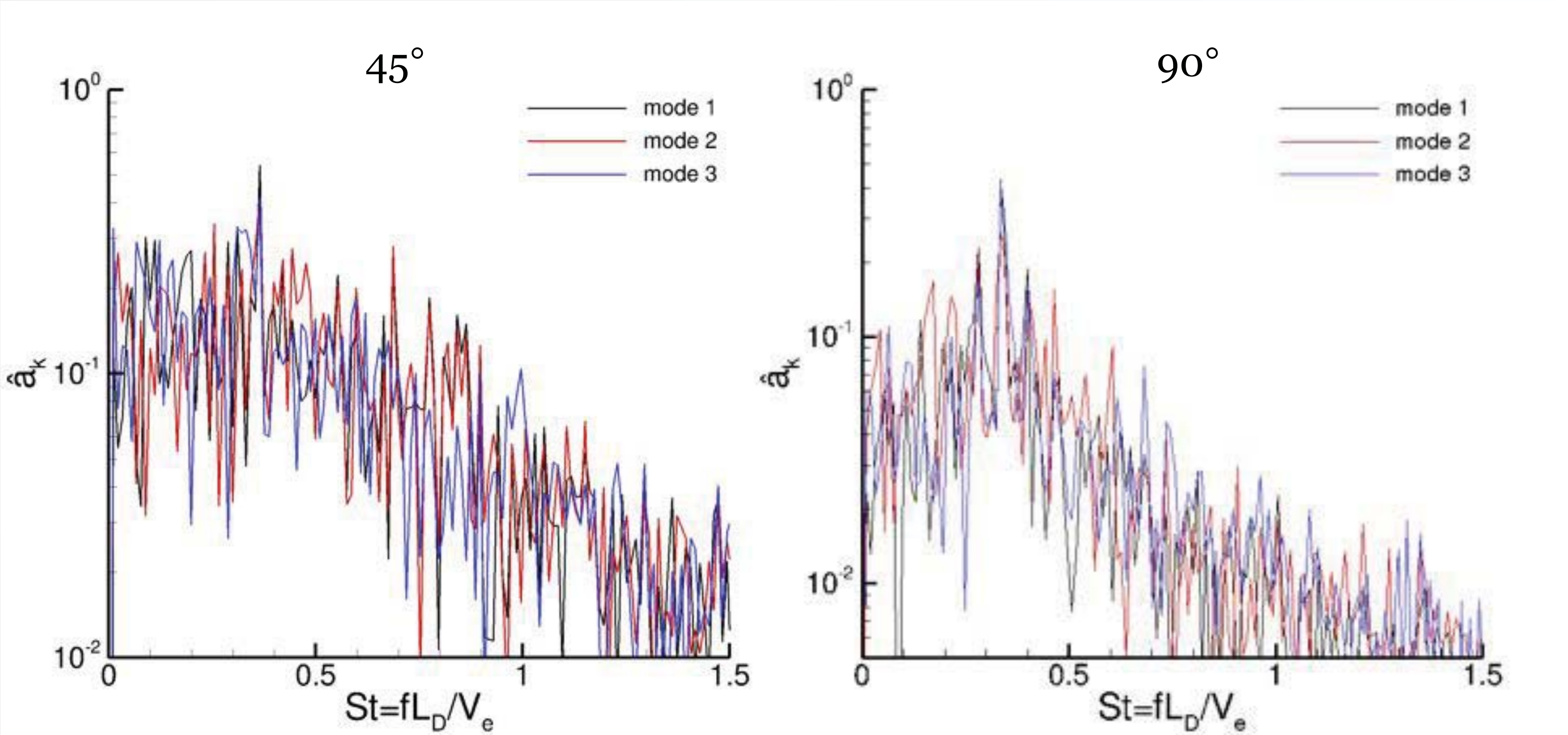
Jet Impingement Problem:

POD modes



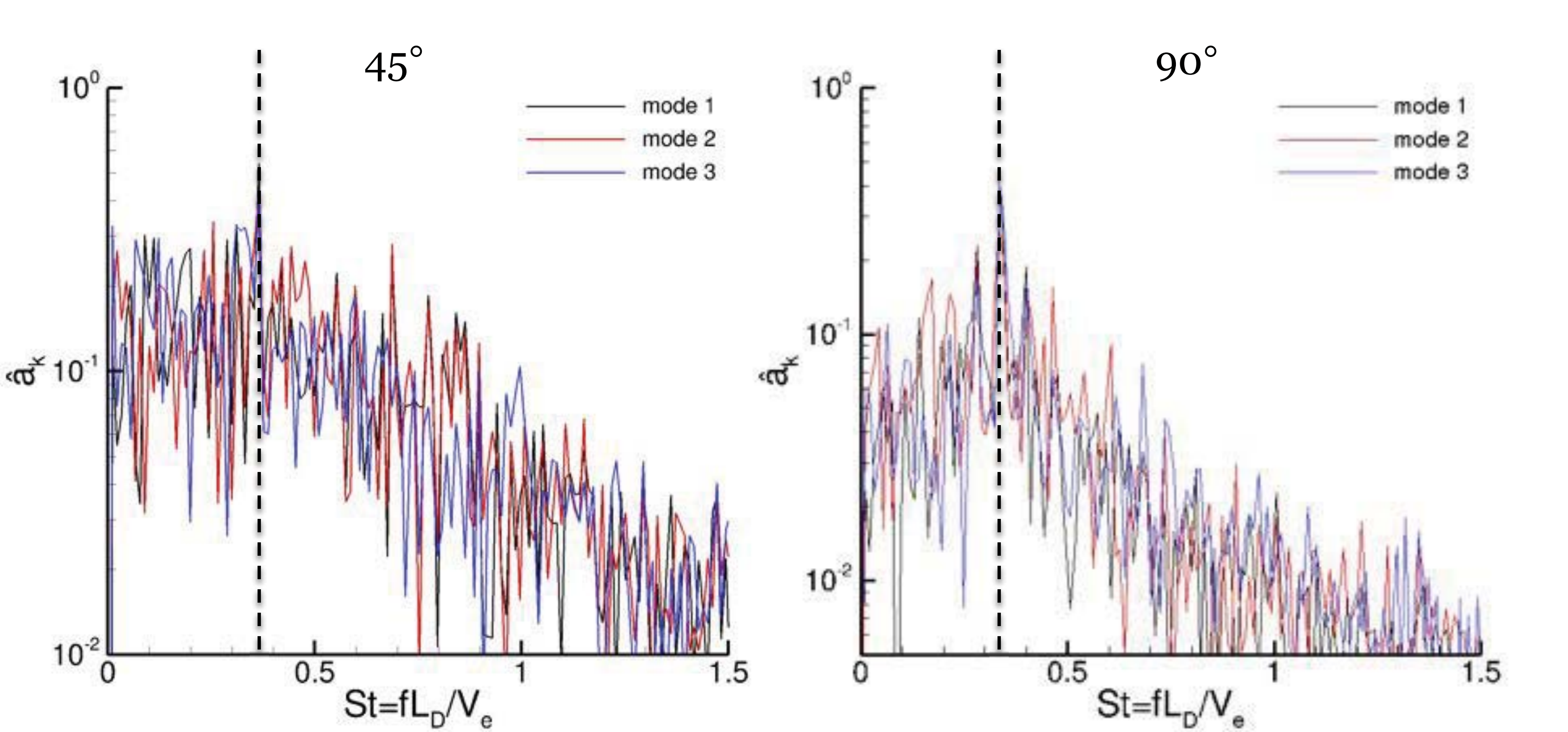
Jet Impingement Problem:

Time Coefficients



Jet Impingement Problem:

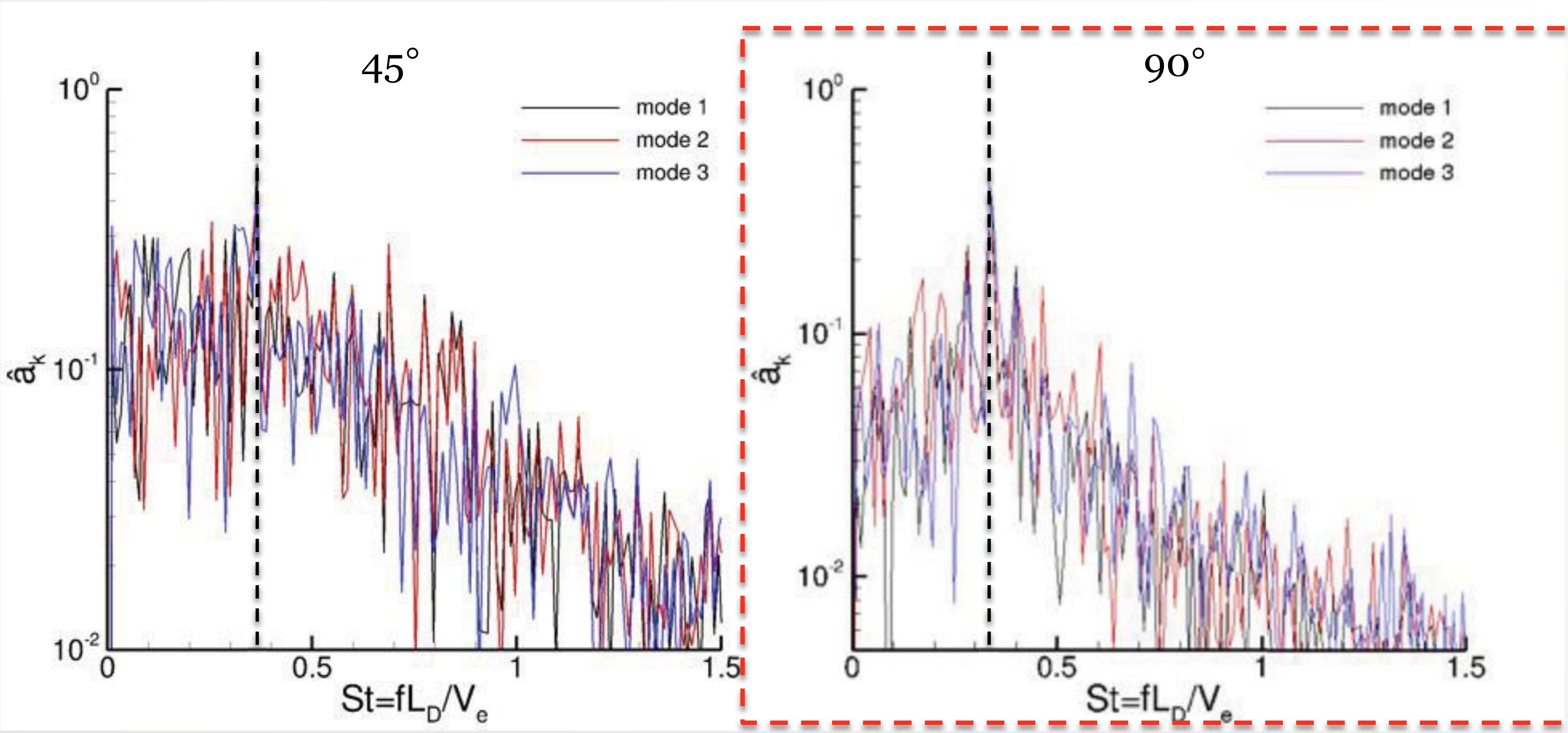
Time Coefficients



- Dominant frequencies, St≈0.36 and 0.33, for 45° and 90°, respectively
- Dominant frequency occurs for all three modes

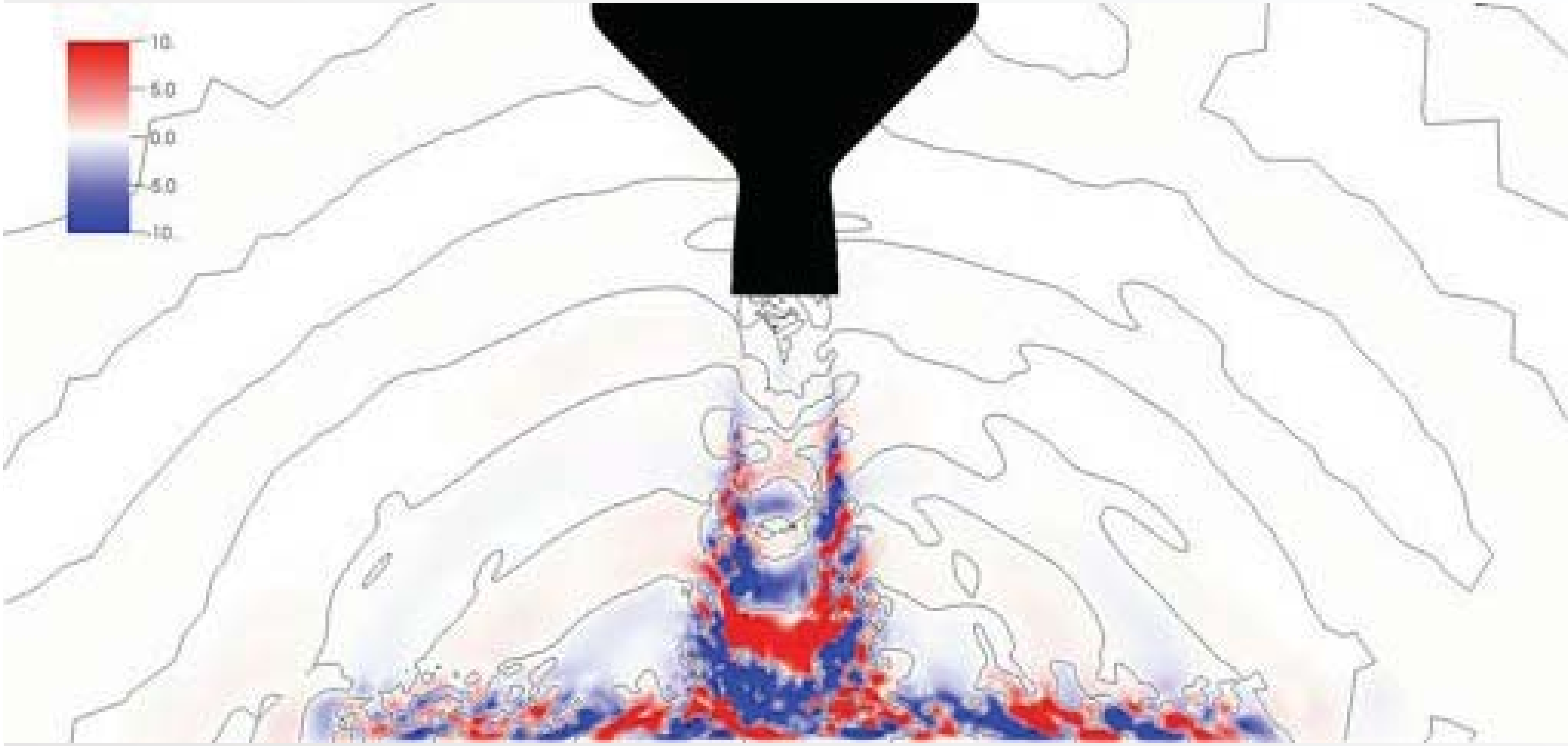
Jet Impingement Problem:

Time Coefficients



- Dominant frequencies, St≈0.36 and 0.33, for 45° and 90°, respectively
- Dominant frequency occurs for all three modes

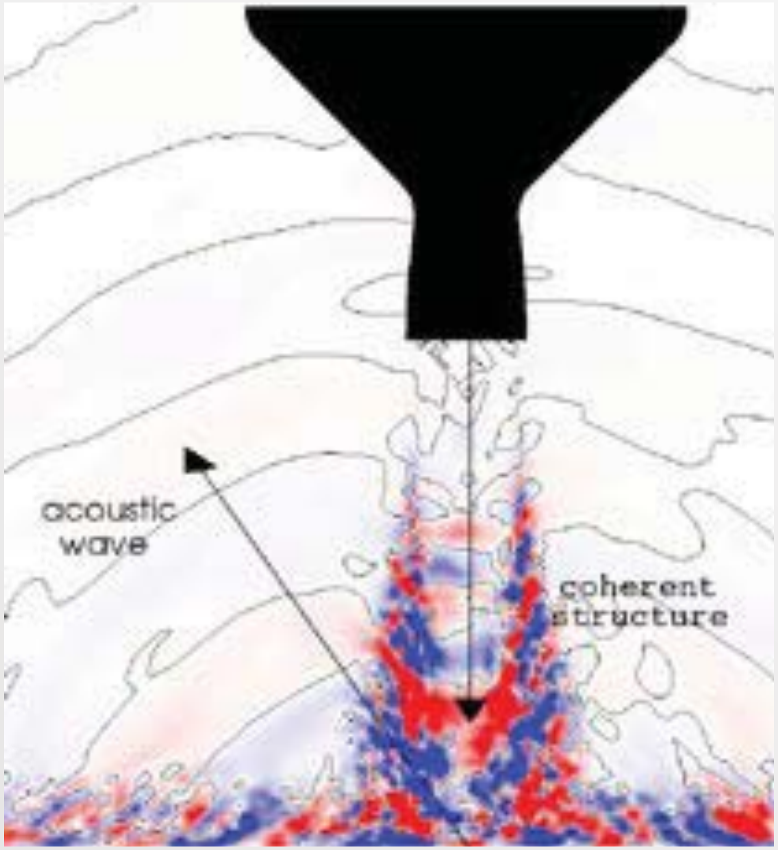
Phase-Averaged U'-Velocity



- Phase-averaged at St ≈0.33

Jet Impingement Problem:

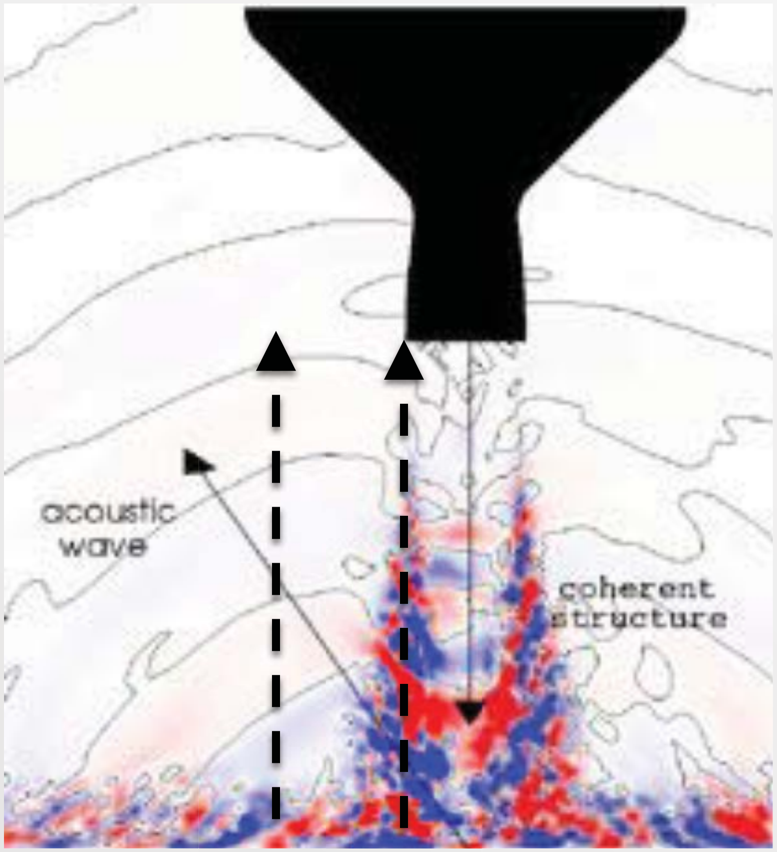
Spectral Analysis



- Downstream convected coherent structures interact with shock oscillations
- Generated acoustic waves excite shear layer

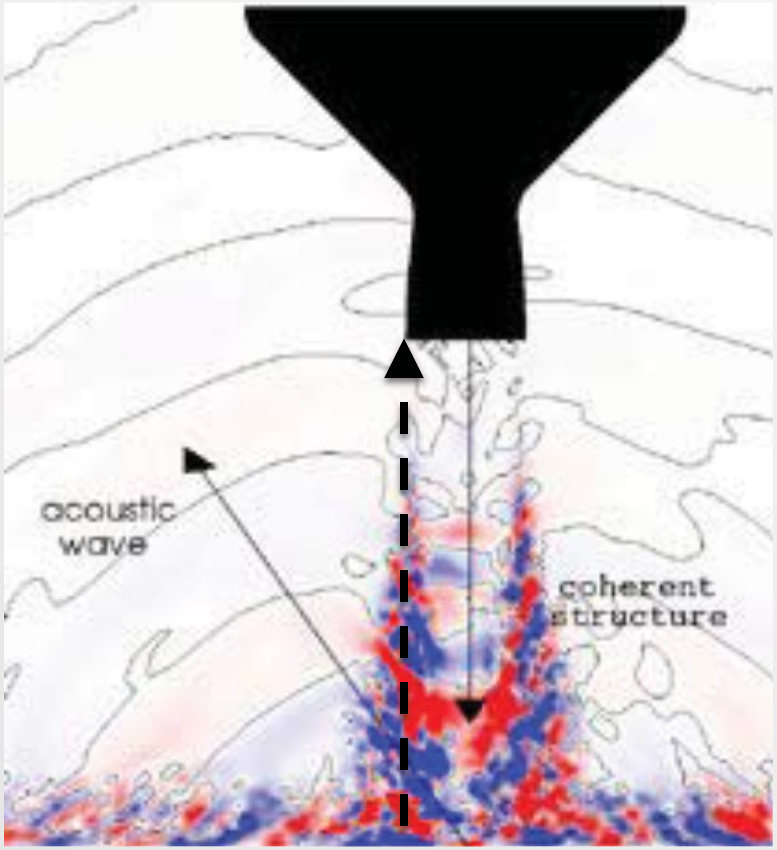
Jet Impingement Problem:

Spectral Analysis



- Extract Fourier spectra along two lines
  (1) shear layer region
  (2) 1xD away from nozzle lip

Spectral Analysis



- Extract Fourier spectra along two lines
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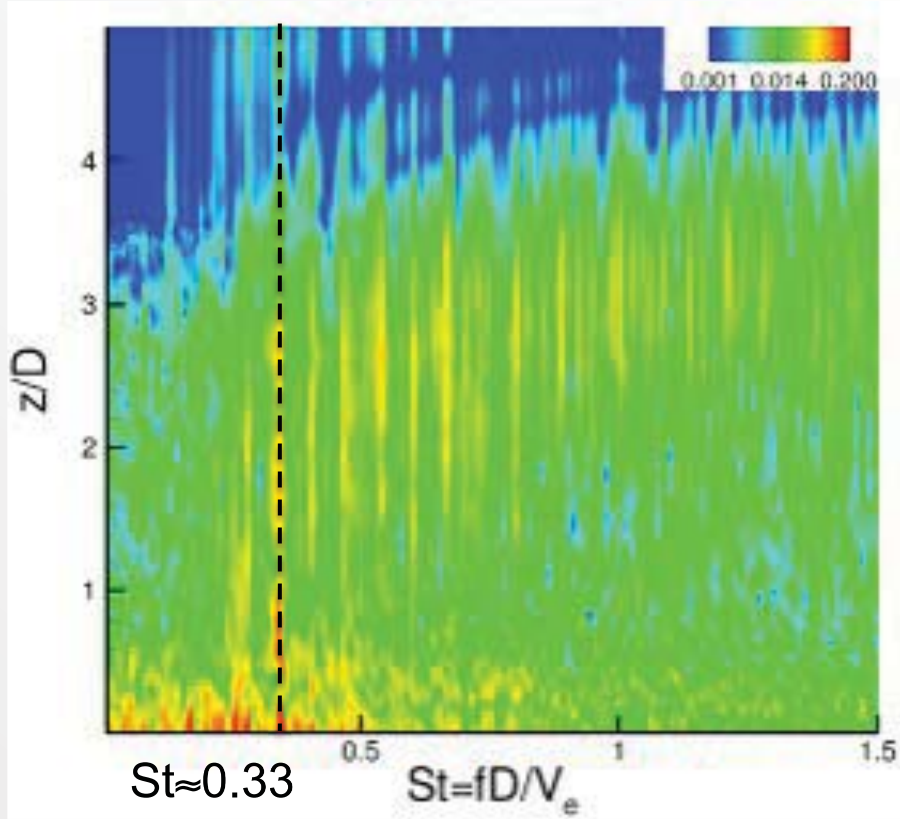
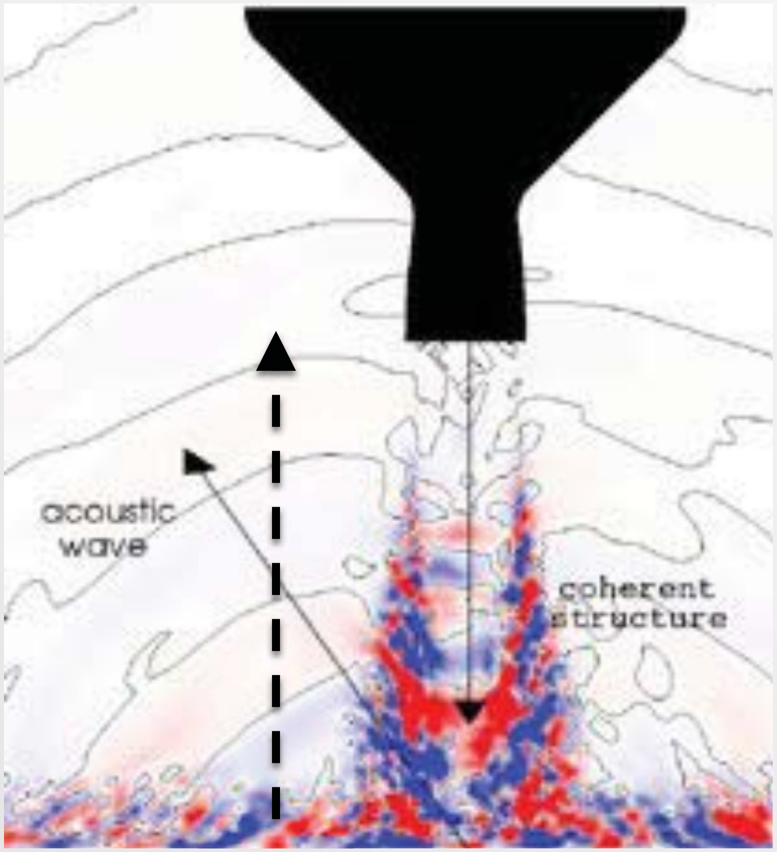
Fourier spectrum



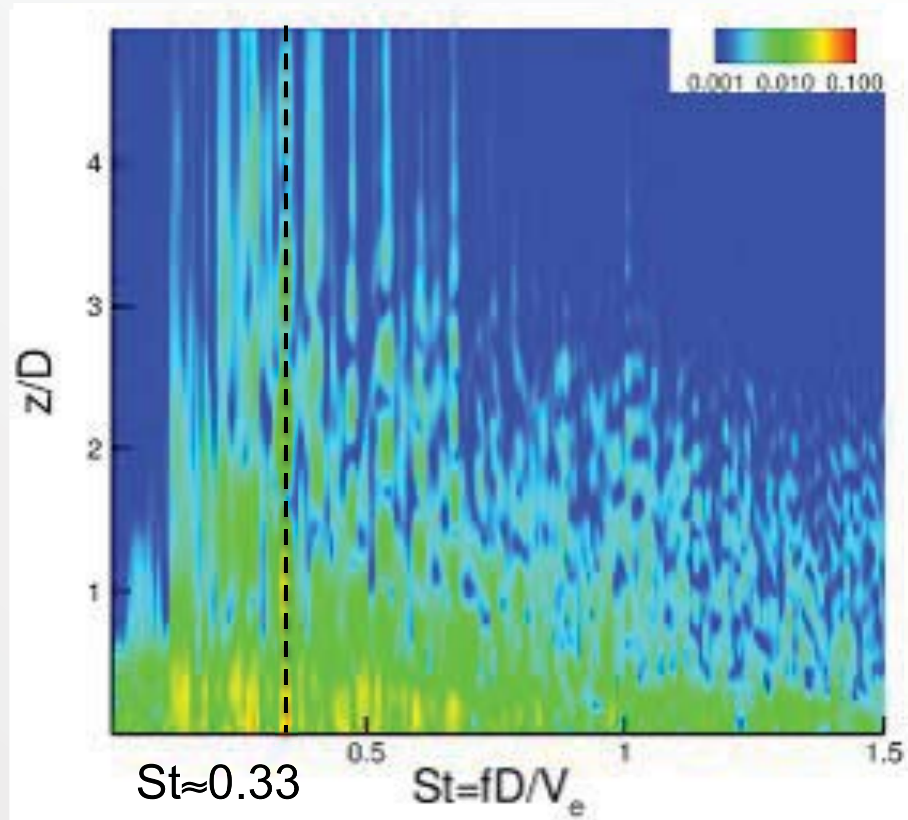
- Frequency (St≈0.33) dominant for all vertical distances, z/D=1-5
- High frequencies in spectrum generated by linear and nonlinear mechanisms
- Low frequencies mainly due to shock oscillations

Jet Impingement Problem:

Spectral Analysis



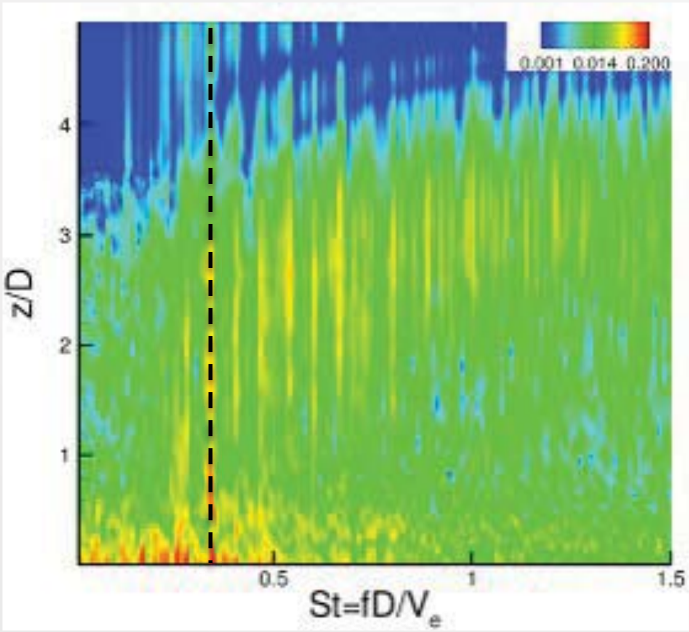
Fourier spectrum

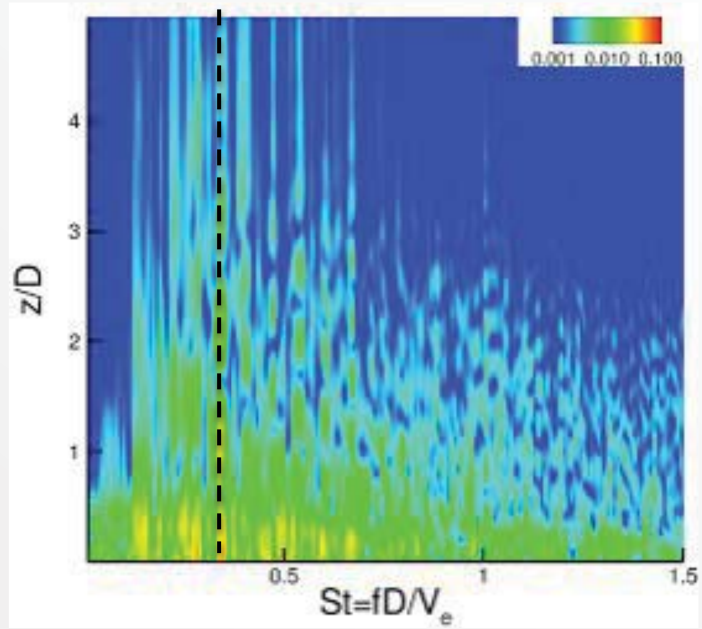


- Extract Fourier spectra along two lines
  (1) shear layer region
  (2) 1xD away from nozzle lip
- Dominant frequencies correspond to each other for (1) & (2)

Jet Impingement Problem:

Feedback Mechanism?





Yes:

- Strong correlation between frequency spectra

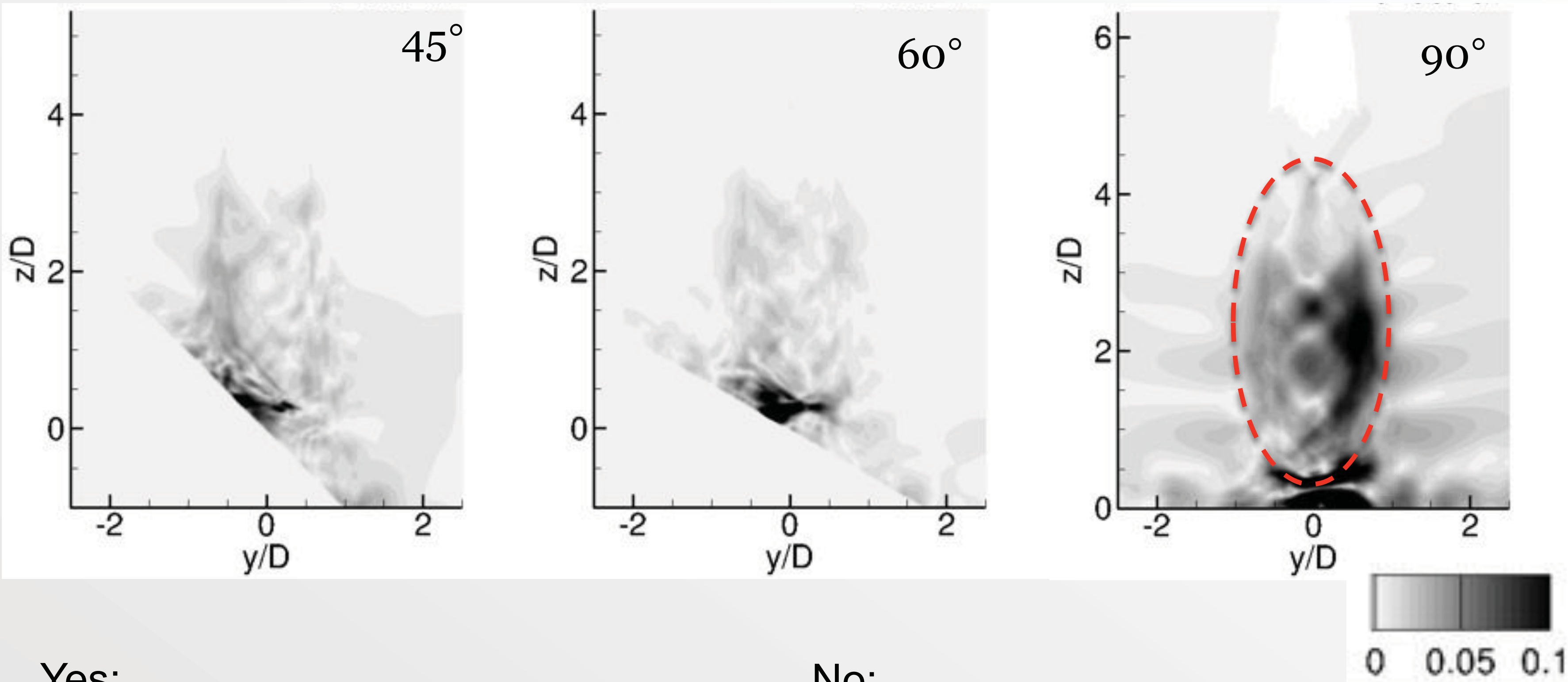
No:

- Unsteady coherent structures generate pressure waves
- Numerical noise

Jet Impingement Problem:

Feedback Mechanism?

Pressure amplitude from DFT for St=0.41



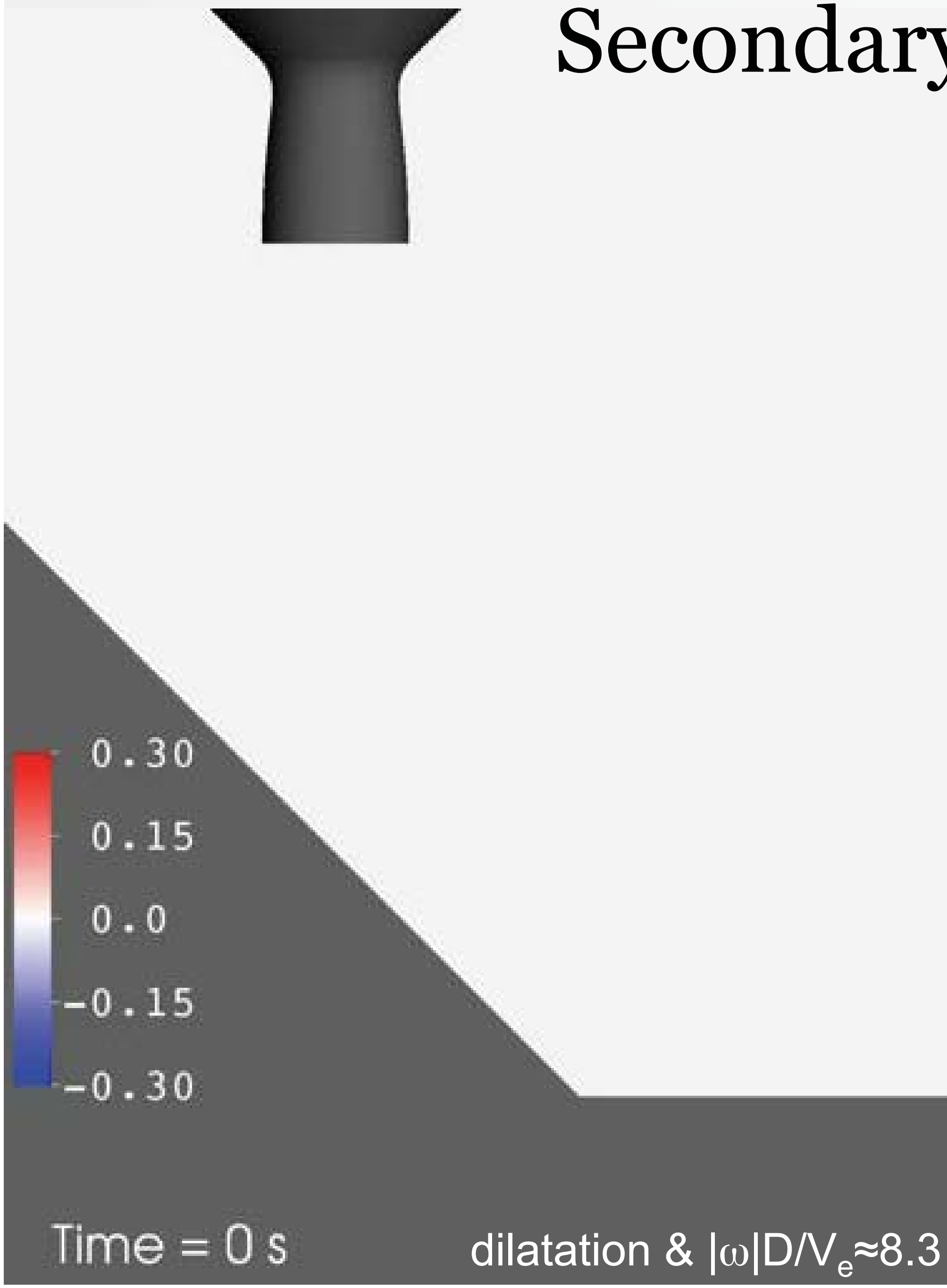
Yes:

- Strong correlation between frequency spectra
- Strong "Upstream" effect in pressure amplitudes values

No:

- Unsteady coherent structures generate pressure waves
- Numerical noise

Secondary Impingement

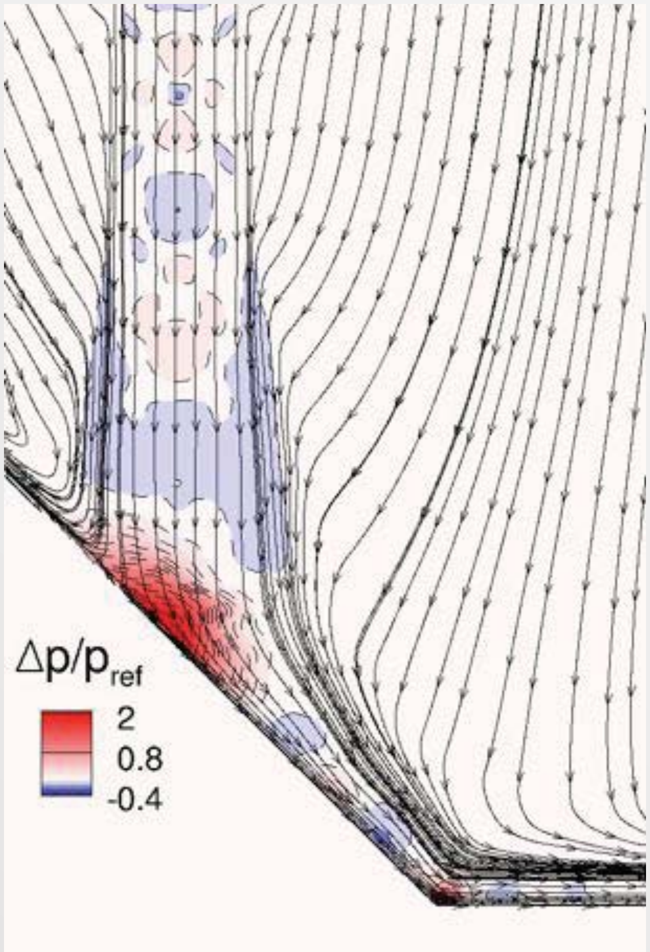


- Most fundamental studies focus on plate impingement without a horizontal plate
- Why is this important?
  - Most flame deflectors at KSC are shaped this way
- Flow physics are strongly affected by horizontal plate
  - Acoustics
  - Jet primary and secondary shock interactions

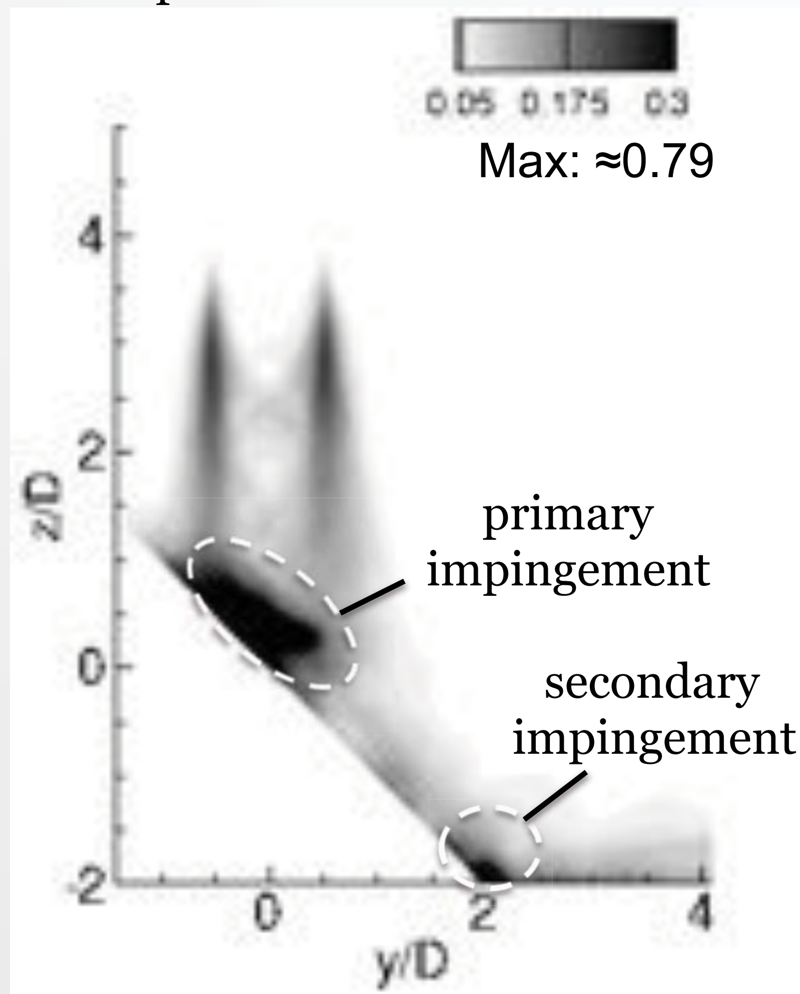
Jet Impingement Problem:

Secondary Impingement

Mean pressure and streamlines



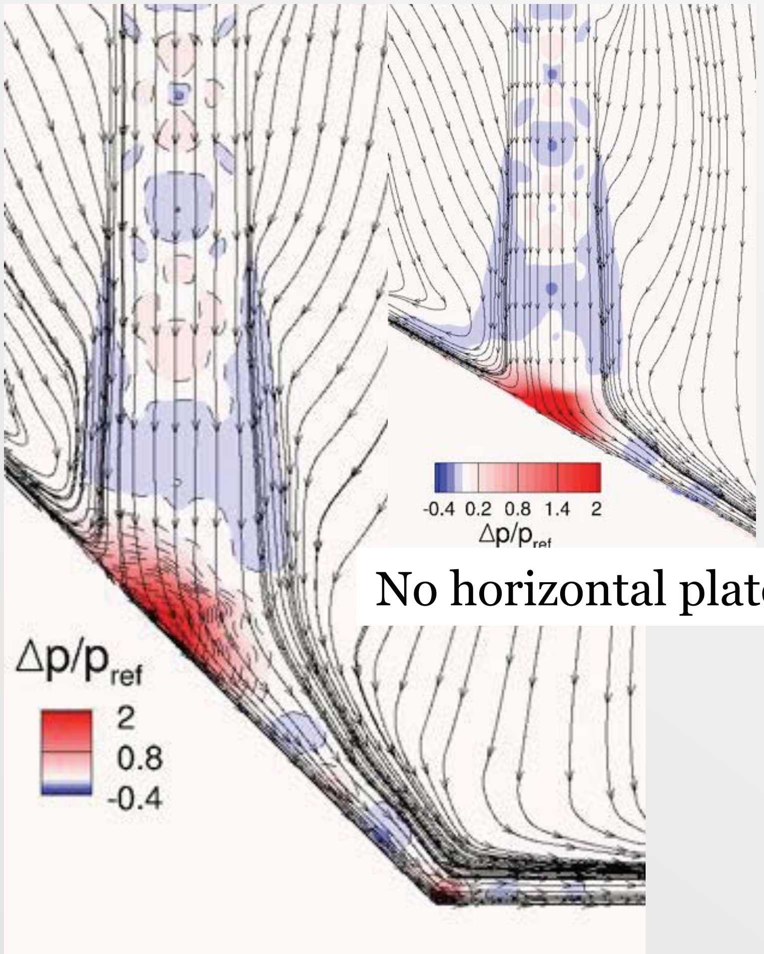
rms pressure



- Strong unsteadiness at primary and secondary impingements
- Roughly 20% larger peak pressure rms values

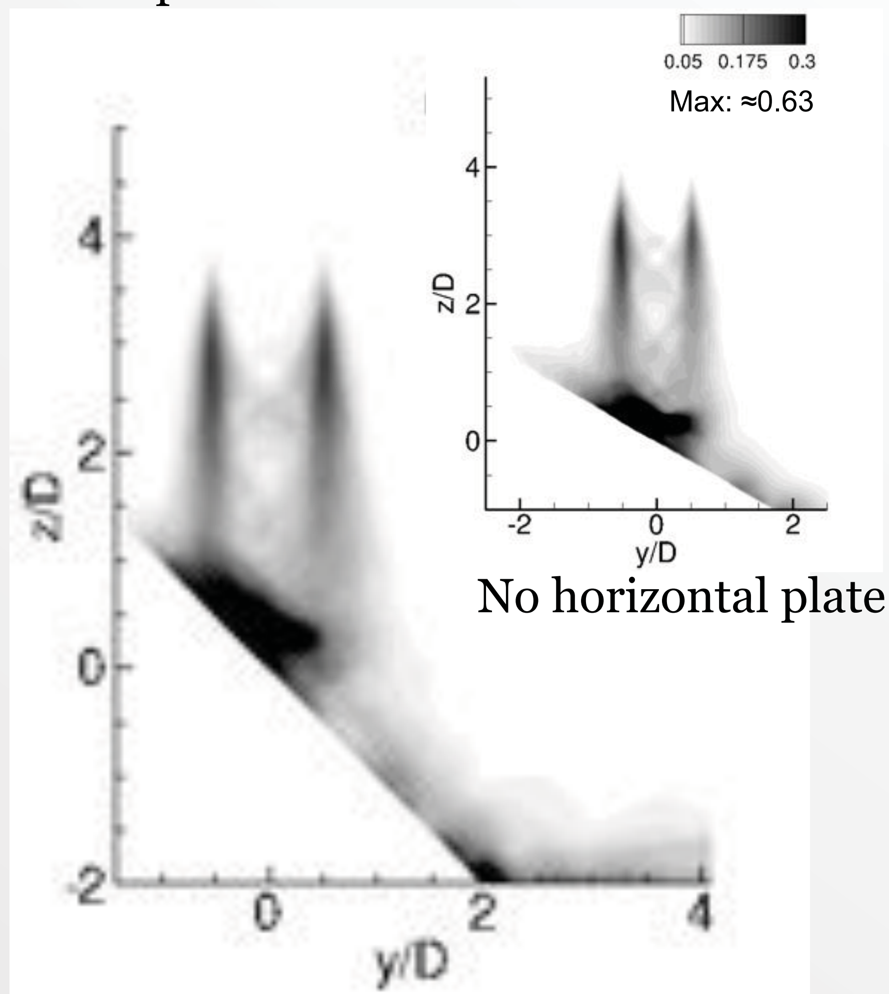
Secondary Impingement

Mean pressure and streamlines



No horizontal plate

rms pressure



No horizontal plate

- Strong unsteadiness at primary and secondary impingements
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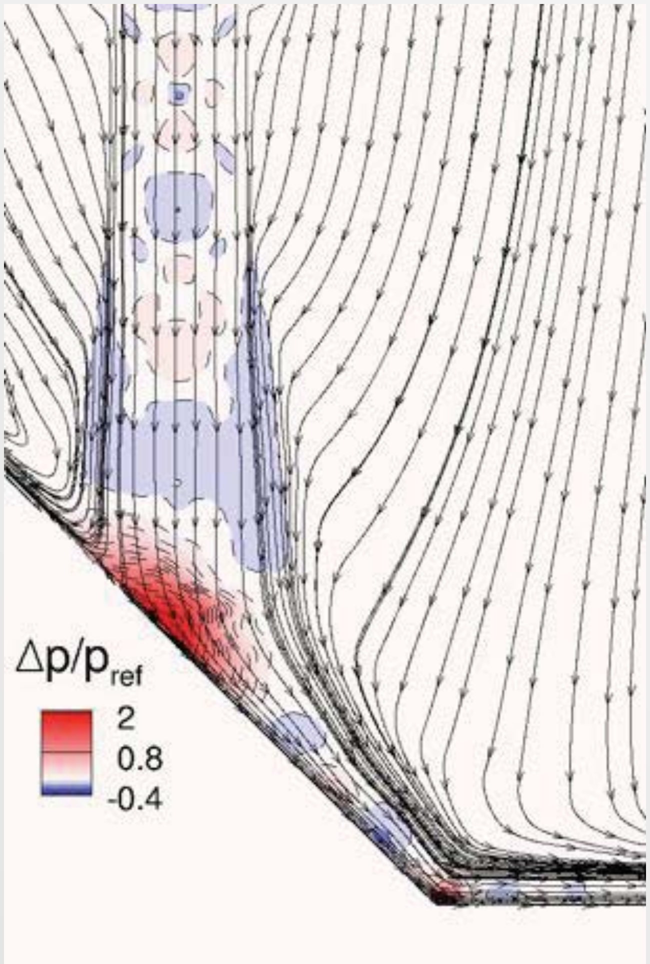
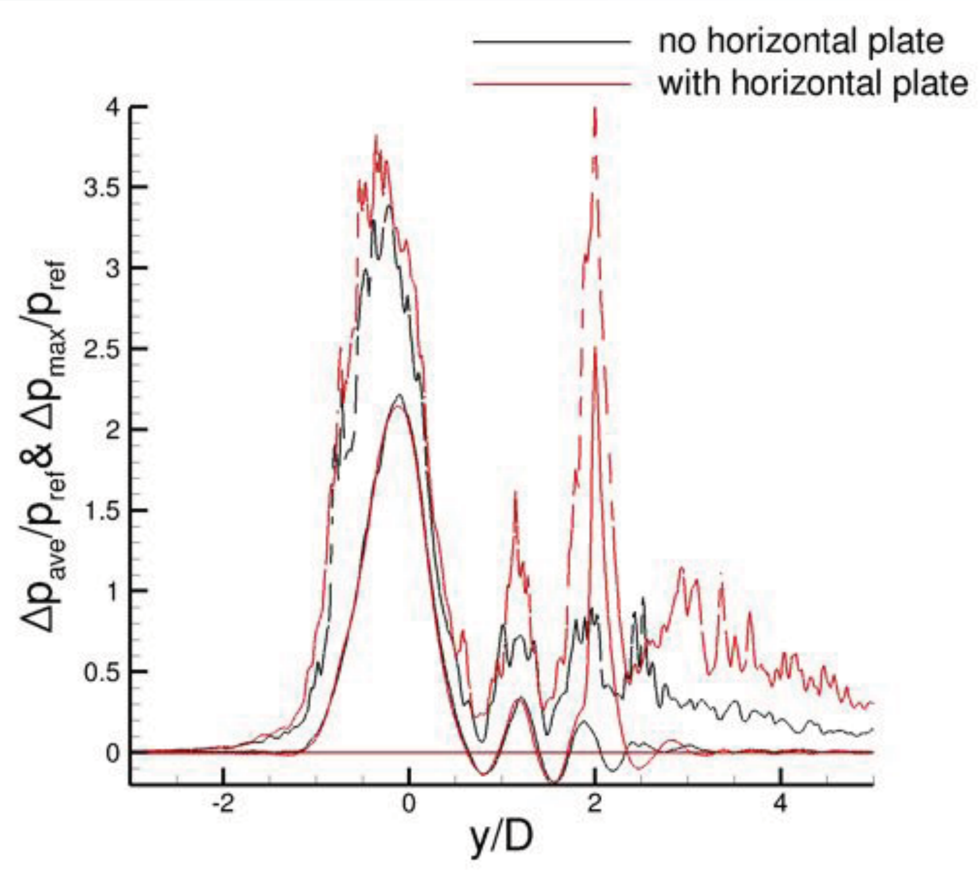
Jet Impingement Problem:

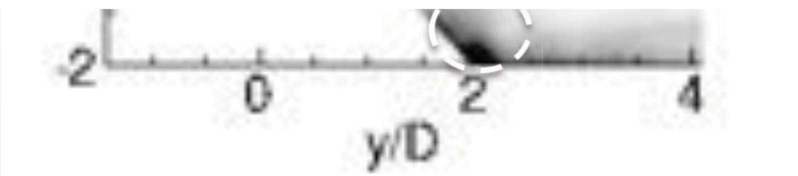
Secondary Impingement

Mean pressure and streamlines



Maximum pressure

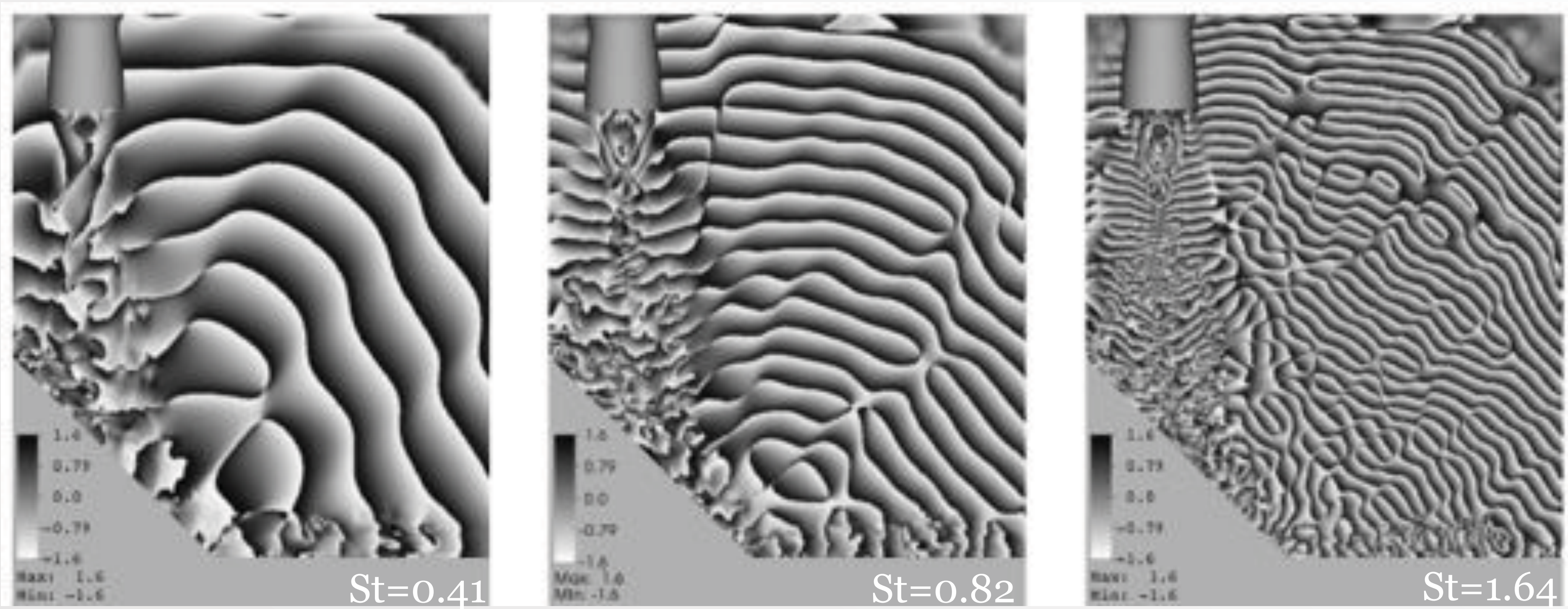




- Strong unsteadiness at primary and secondary impingements
- Roughly 20% larger peak pressure rms values

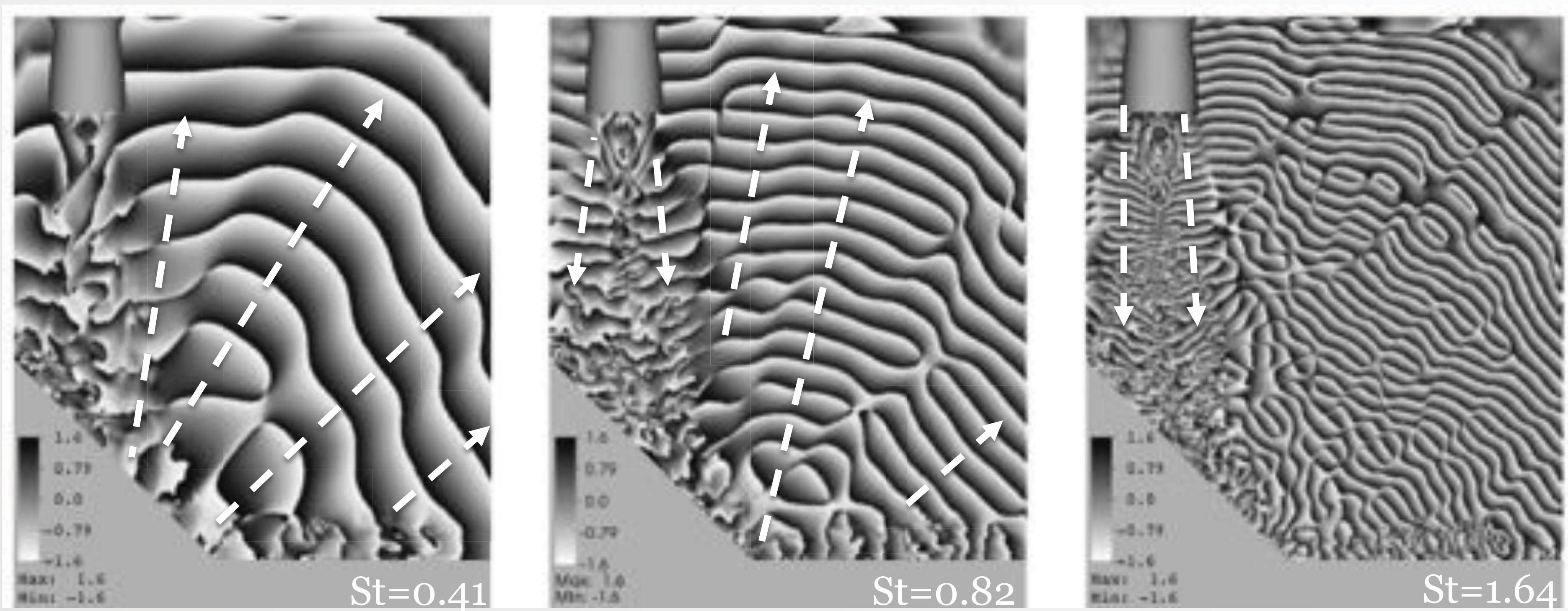
Secondary Impingement (SI)

Spectral Analysis: Phase



Secondary Impingement (SI)

Spectral Analysis: Phase

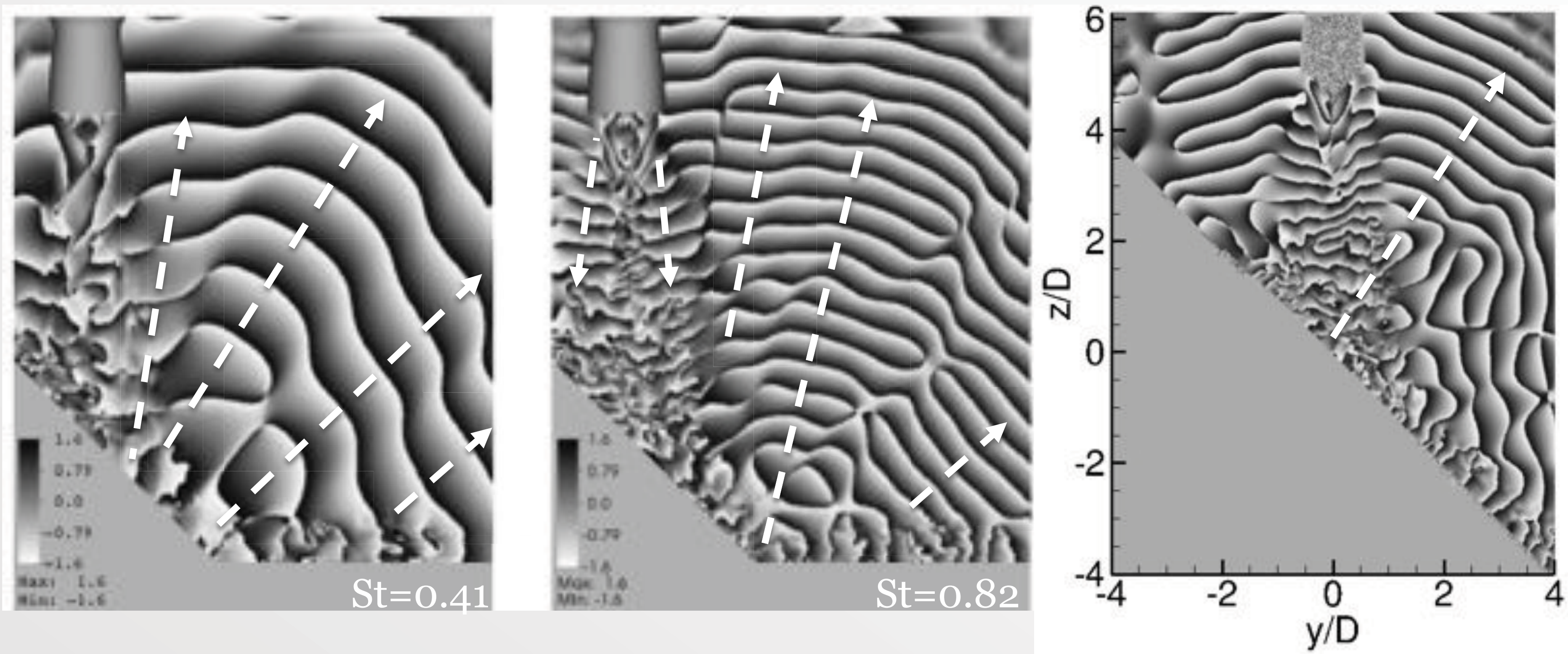


- SI strongly affects acoustic near field
- SI seems to have affect on shear layer unsteadiness

Secondary Impingement (SI)

Spectral Analysis: Phase

no horizontal plate



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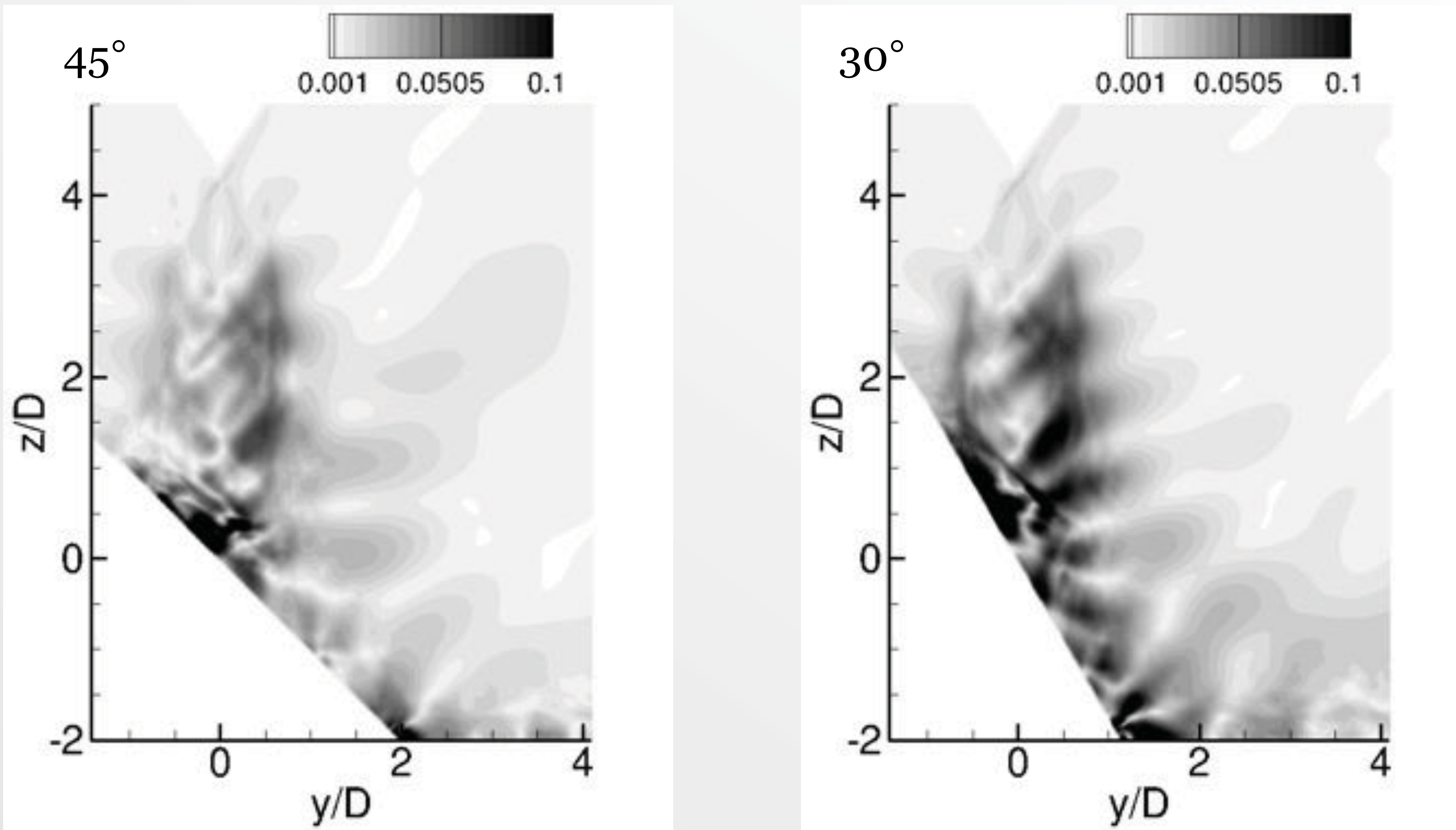
Secondary Impingement

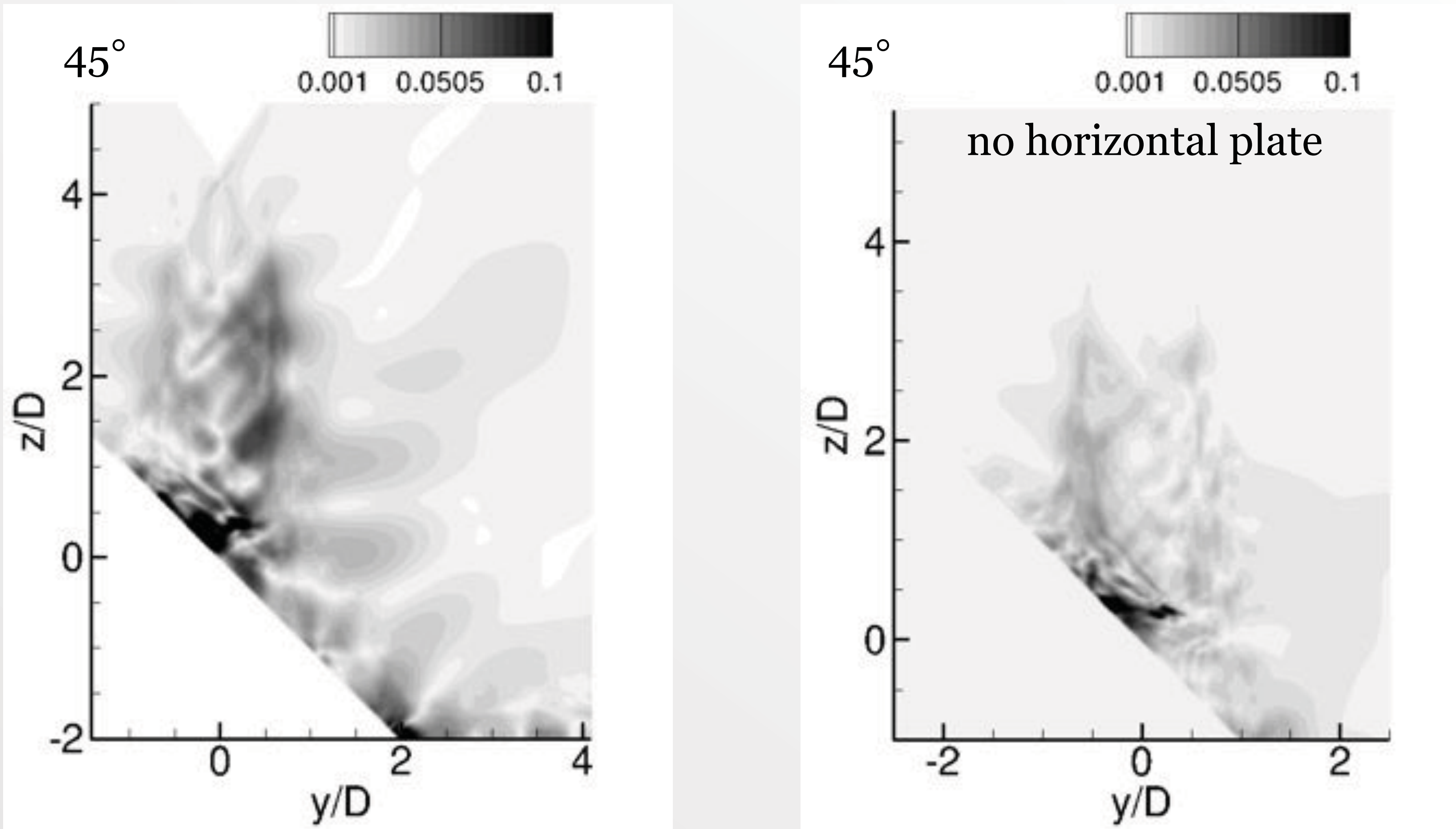
Pressure amplitudes from DFT for St=0.41



- Strong upstream effect of secondary impingement
- horizontal impingement plate is crucial for flame deflector analysis

Secondary Impingement

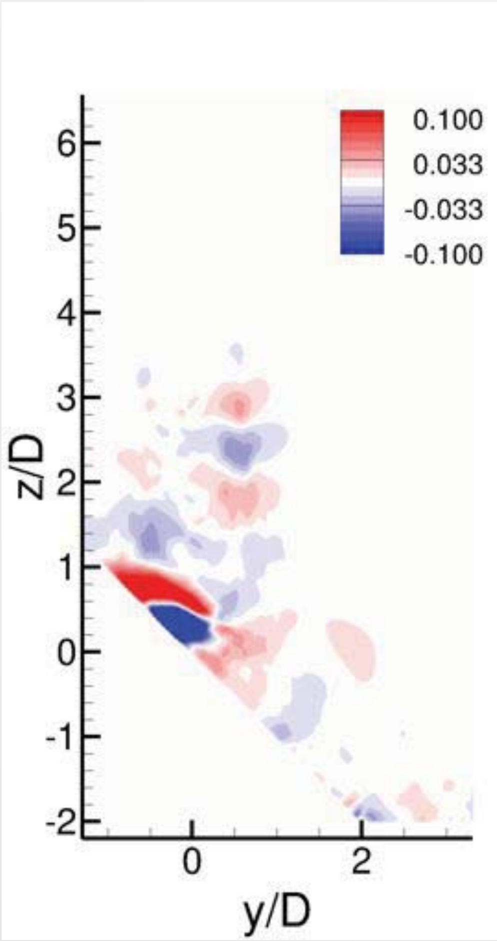
Pressure amplitudes from DFT for St=0.41



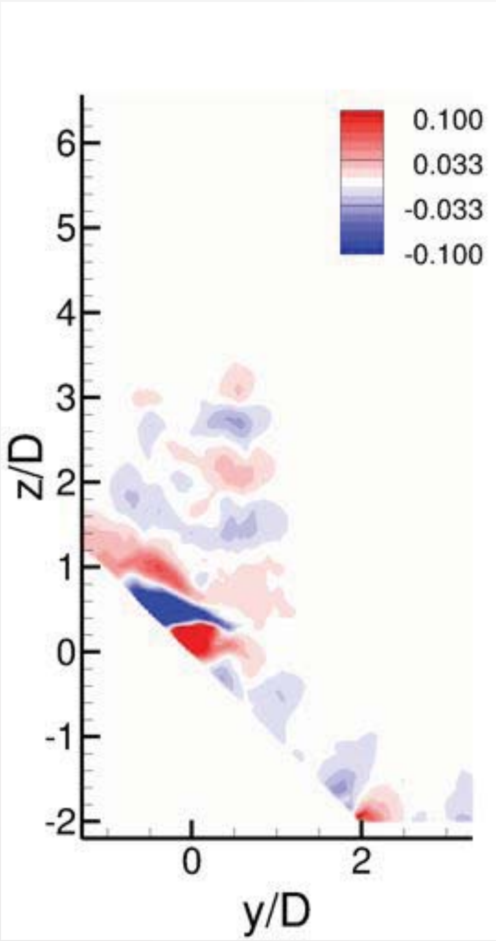
- Strong upstream effect of secondary impingement
- horizontal impingement plate is crucial for flame deflector analysis

Secondary Impingement

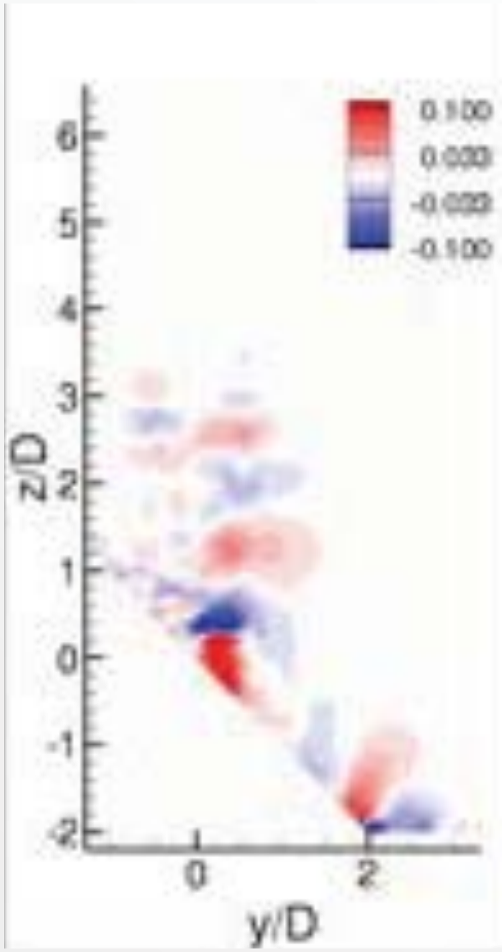
Proper Orthogonal Decomposition (45°)



mode 1



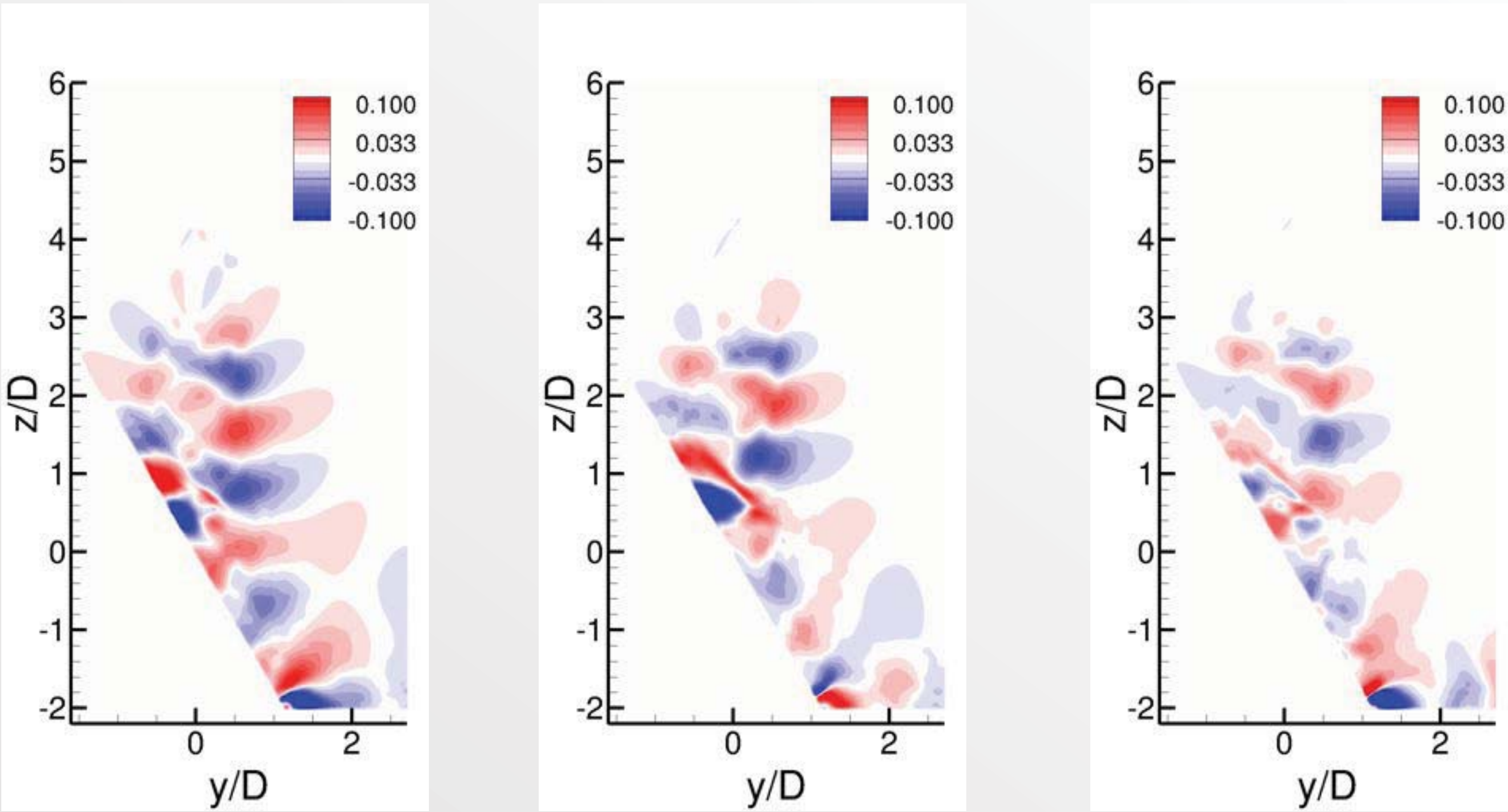
mode 2



mode 3

Secondary Impingement

Proper Orthogonal Decomposition (30°)



mode 1 mode 2 mode 3

Outline

Motivation/Introduction

Introduction to the launch environment flow and jet impingement problem.

Computational Methods

Overview of tools and setup used for simulations.

Jet Impingement Model Problem

Analysis of jet impingement problem.

Falcon Heavy: Pressure Environment

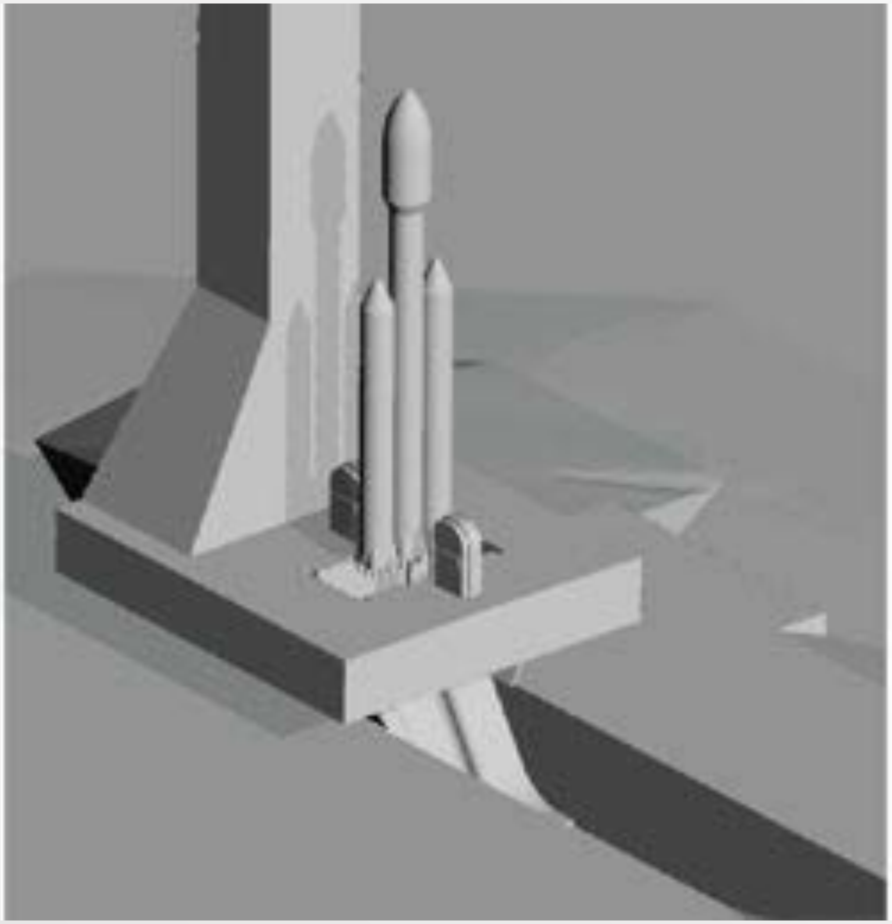
Final application of pressure environment analysis.

Summary & Future Work

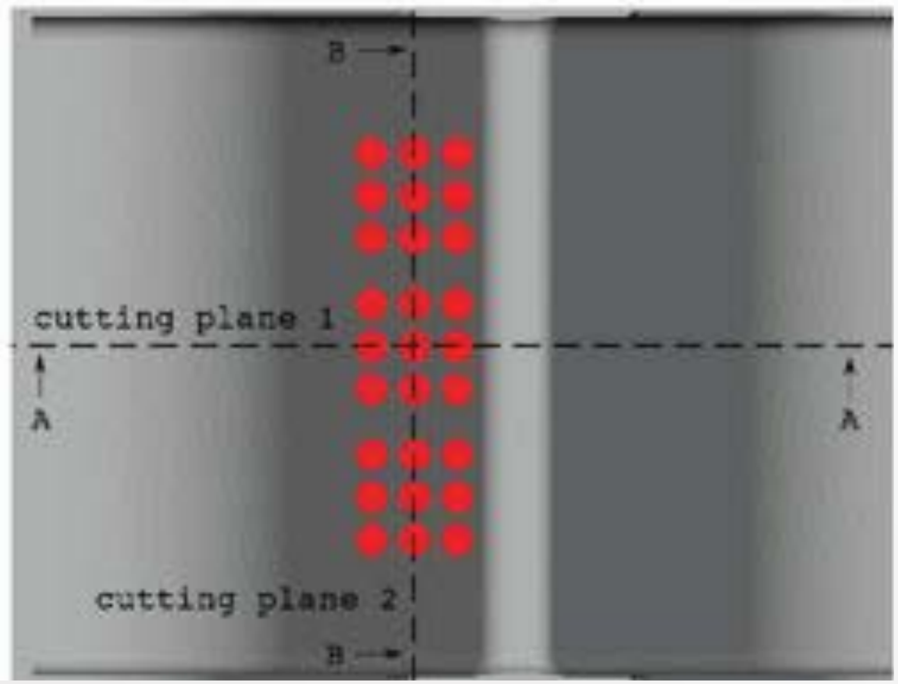
Overview of results and what tasks lie ahead.

Jet Impingement Problem:

Computational Setup



Cutting Planes

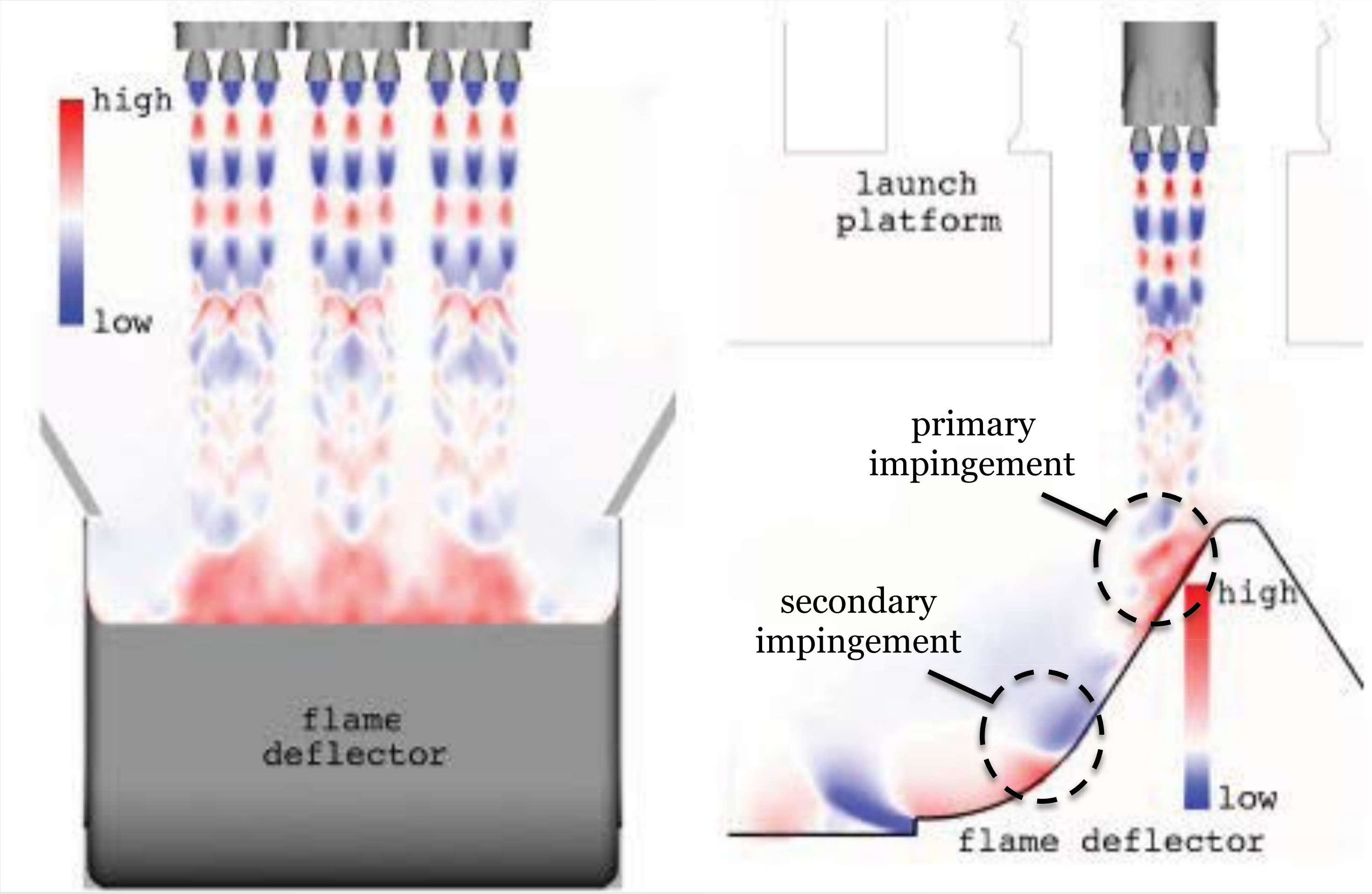


Computational Setup:

- 50 billion grid points needed to obtain similar grid resolution as for model problem, 150 million grid points used here → 23 grid points per nozzle diameter
- multi-species calculation, hot jet, inviscid, slip BCs
- 27 Merlin engines

Jet Impingement Problem:

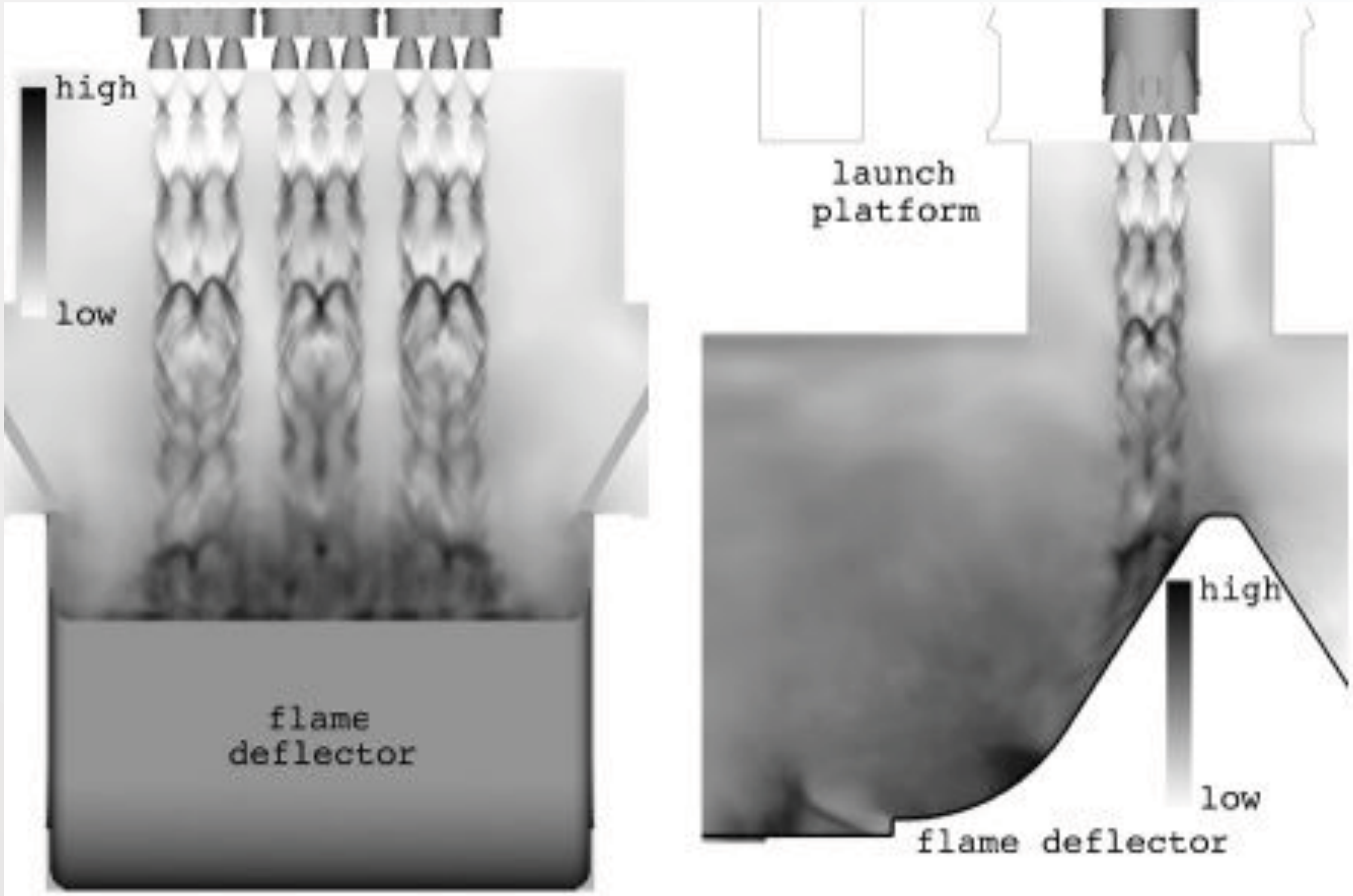
Mean Pressure



- Jet interaction
- Primary and secondary impingement pressure
- Step cannot be modeled with slip wall BCs

Jet Impingement Problem:

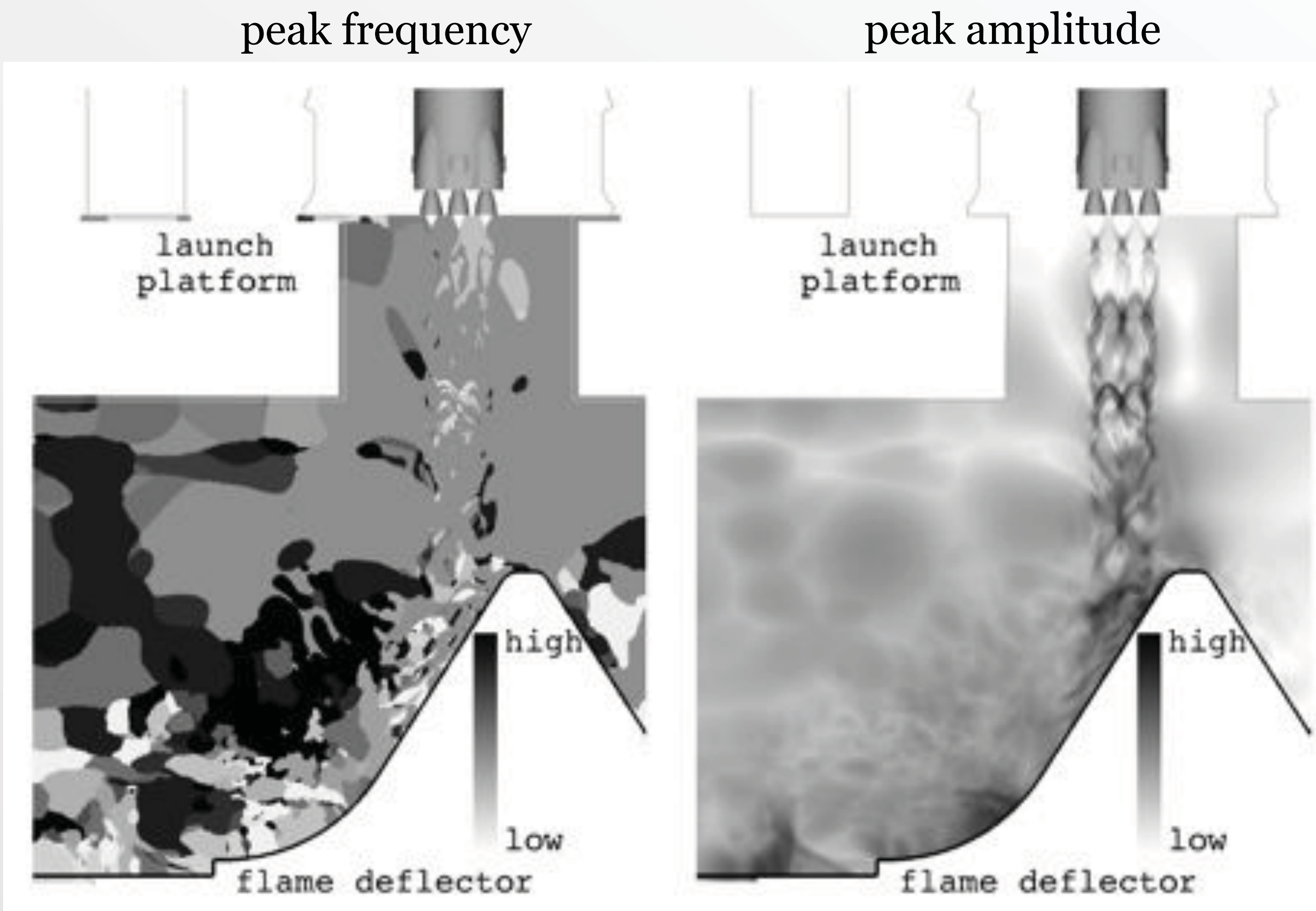
Pressure RMS Values



- High pressure rms values in Mach diamond structure
- Strong unsteadiness at primary and secondary impingement locations

Jet Impingement Problem:

Spectral Analysis

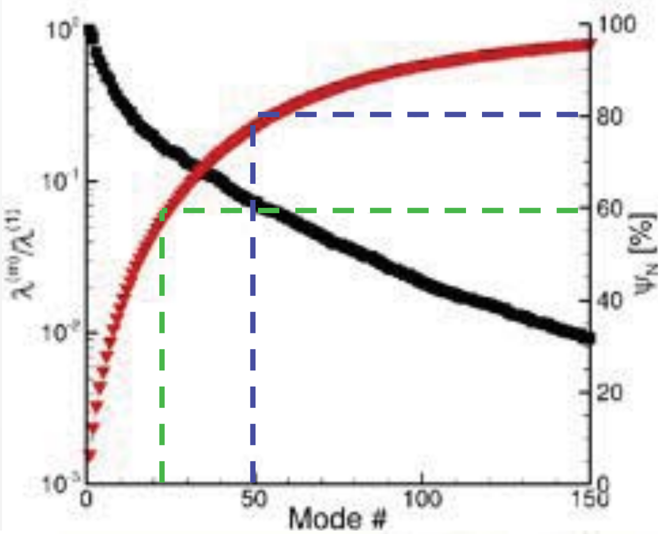


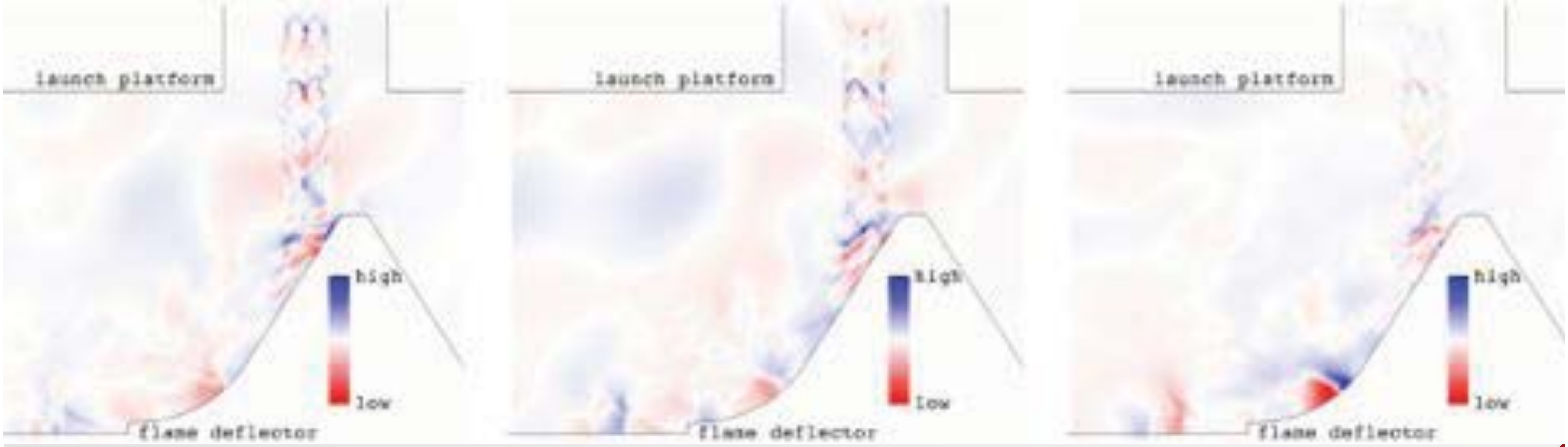
- Low frequency content at impingement locations
- High frequencies right above high pressure region
- Duct pressure oscillations due to containment

Jet Impingement Problem:

Proper Orthogonal Decomposition

- Interaction between jets and primary impingement
- 3rd POD mode picks up secondary impingement
- Strong coherence suggest use of ROMs
- Coherence may be over-emphasized due to low grid resolution





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Falcon Heavy: Pressure Environment

Final application of pressure environment analysis.

Summary & Future Work

Overview of results and what tasks lie ahead.

Summary

Computational Approach:

- slip wall BC valid assumptions for this problem
- Similar pressure signatures for inviscid, ILES, DES

Jet Impingement Model Problem:

- Significant unsteadiness needs to be captured by CFD
- ILES captures unsteadiness until St≈3-4
- Strong coherence in flow field: f_{low} and f_{high}
- POD provides insight about unsteadiness of shock oscillations
- 90°: Strong interaction of shock oscillations with unsteadiness of jet
  ➔ Feedback mechanism
- SI plays important role for pressure field on flame deflector
- SI effects unsteadiness of jet in near field
  ➔ Feedback mechanism

Falcon Heavy:

- Similar flow physics as in impingement model problem
- Interaction between Mach diamond structure and shock oscillations

Future Work

Jet Impingement and Secondary Model Problems:

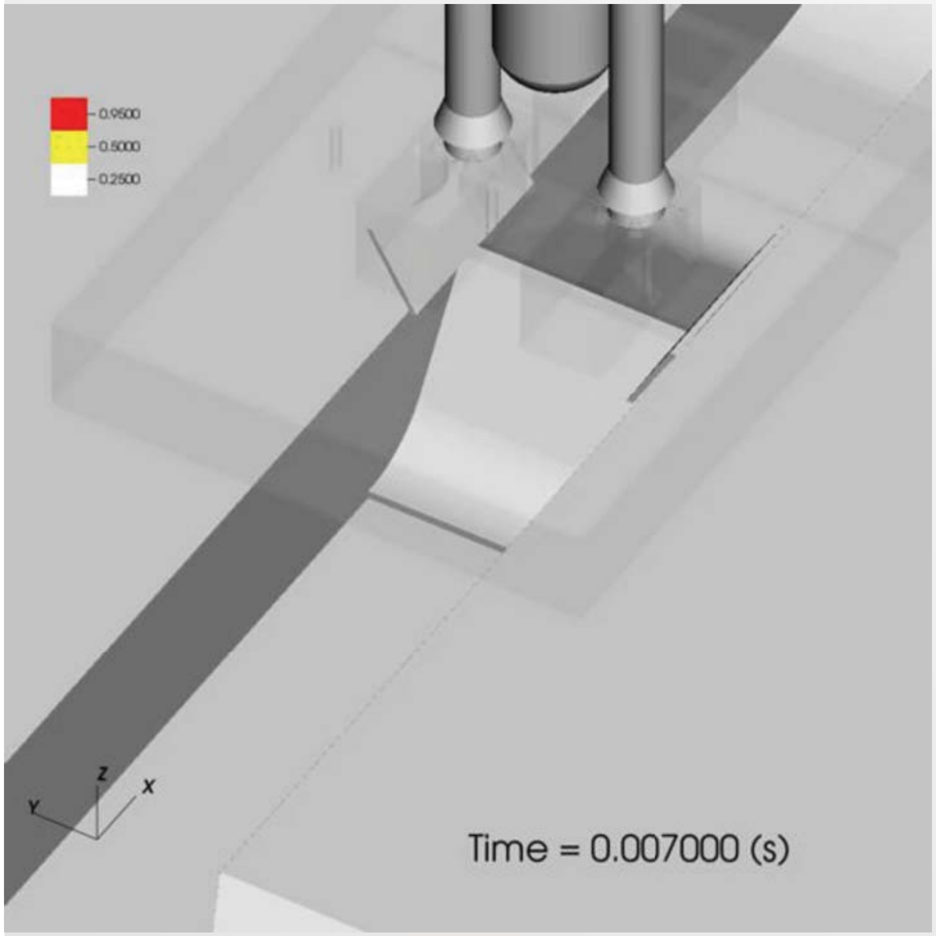
- Analyze transition process (azimuthal mode decomposition)
- Capture interaction between shock oscillation and jet flow by employing LST analysis
- 3D POD
- Use higher-order methods to capture higher-frequencies
- Reduced order model based on POD or disturbance flow formulation

Falcon Heavy:

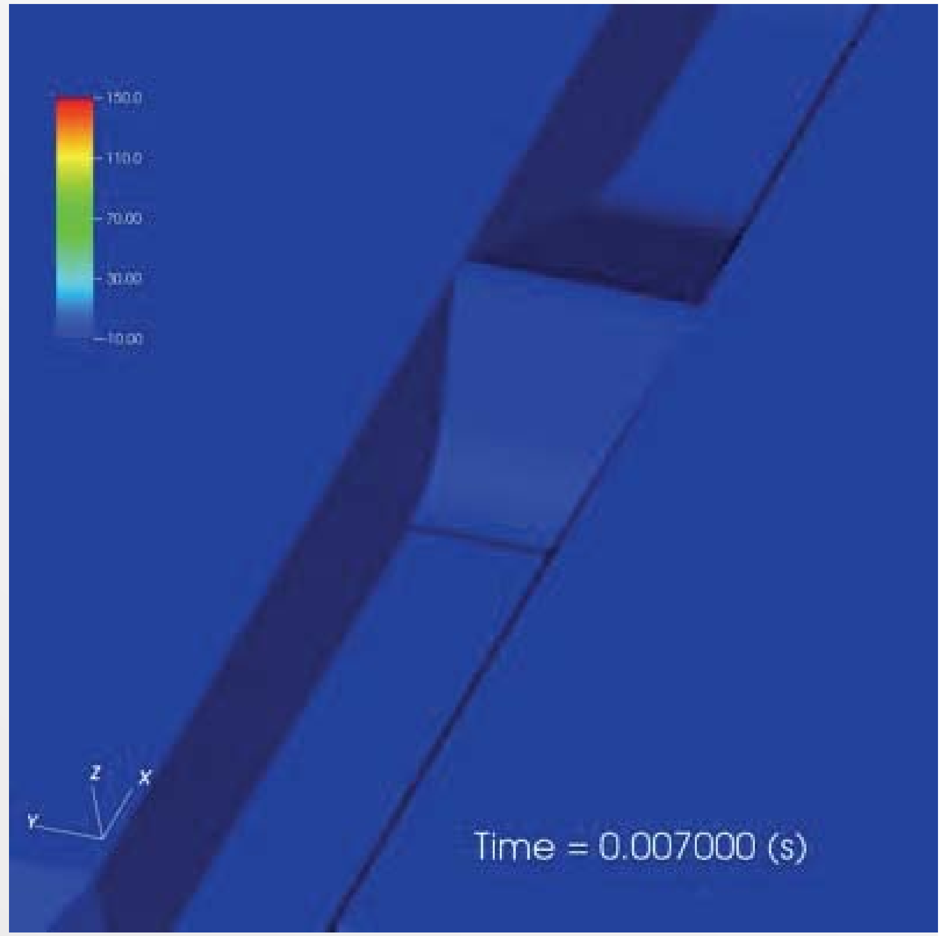
- Utilize ROMs to predict pressure field

Thank you for your attention!

STS-135



exhaust gas mass fraction



surface pressure contours